

“The Number Race”: an efficacy study of an adaptive software in 5-to-7-year-old New Zealand children with low numeracy.

A thesis submitted in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE IN PSYCHOLOGY

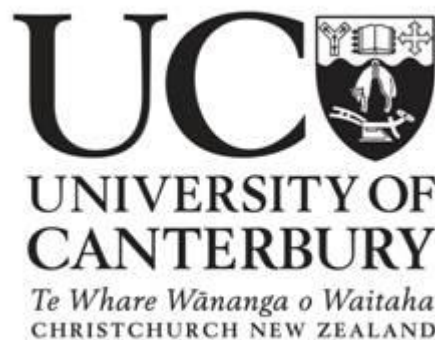
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ABSTRACT

Computer-assisted interventions designed to remediate low numeracy and developmental dyscalculia (mathematical learning disability) have been utilised in preschools and kindergartens with some efficacy for over thirty years (Clements, 2002). A recent development in this field is ‘adaptive game’ technology, which adapts task difficulty online as children learn. *The Number Race* is the first such package for mathematics. Previous efficacy studies suggest its use results in an improvement in core measures of early numeracy, such as speed at enumerating 1-3 objects (subitizing) and comparison of numerals and groups of objects. The present study tested the efficacy of a new version of *The Number Race* (version 3.0) using New Zealand English and incorporating new instructional factors, in a younger population than most previously tested. Participants were twelve 5-to-7-year-old children and a typically developing control group matched on age and sex ($n = 12$). Following pre-testing using standardised tests and a computerised battery, children in the intervention group used *The Number Race* for twenty minutes each school night, for one month. Post-testing results showed that there was a significant improvement in counting and subitizing speed for the intervention group. Participants also became faster and more accurate at comparing numerals. There were no significant changes in standardised mathematics scores. The mental number line task did not show any significant differences before and after intervention but a wide variety of patterns and possible use of strategies were revealed. Overall, this new version of *The Number Race* seems to have modest effects in this population.

CHAPTER ONE

INTRODUCTION

1.1 Overview

Understanding and learning about numbers and mathematics requires a variety of cognitive competencies, even at an early age, and is an important skill not only for academic success, but also for everyday activities such as handling money (Henik, Rubinsten & Ashkenazi, 2011; Stith & Fishbein, 1996). However, many general factors such as educational experience, IQ or motivation can affect the development of this skill.

One specific factor that can negatively affect children's acquisition of basic numerical skills is *developmental dyscalculia*, or mathematical learning disability. Developmental dyscalculia (hereafter "dyscalculia") emerges in early primary school, but can continue to affect an individual in all stages of life, including adulthood. It is characterised by difficulties with core number skills such as counting and simple addition (Geary, 1990; Geary, Bow-Thomas & Yao, 1992; Geary, Brown & Samaranayake, 1991; Geary, Hamson & Hoard, 2000; Geary, Hoard, & Hamson, 1999). In adulthood, adults with dyscalculia continue to show basic number difficulties (Wilson et al., 2014), and may struggle with everyday activities involving numbers.

Unlike its more recognised reading counterpart dyslexia, there is a relative lack of experimental research on and public awareness of dyscalculia; this despite its reported prevalence paralleling that of dyslexia (approximately 6%) (Kosc, 1974; Shalev, Auerbach, Manor & Gross-Tsur, 2000). Due to this lack of research, the aetiology of dyscalculia is

much less well known than that of dyslexia. In recent years, however, cognitive neuroscience research on mathematical cognition has allowed the development of aetiological theories.

The two leading theories of dyscalculia are the *core deficit* theory. (e.g. Dehaene, Piazza, Pinel & Cohen, 2003; Wilson & Dehaene, 2007), which is that dyscalculia is due to an impairment in the core non-linguistic (“non-symbolic”) representation of number; and the *access deficit* theory (Rousselle & Noël, 2007), which is that number representation itself is intact, but that dyscalculia is caused by weak connections between number symbols and non-linguistic representation of number. These theories are explained in more detail in subsequent sections.

One form of remediation is that of computer assisted interventions (CAIs), which utilise specially designed software to teach students with learning difficulties. CAIs of various types have been used in classrooms for over thirty years, and have been shown to be an effective tool for early mathematics learning (Clements, 2002). One particular advantage they have over traditional instruction is that they exploit children’s inherent interest in technology, and can be designed to be highly interactive. A recent development in CAI is the *adaptive game*. Adaptive games present learning exercises as a game and adapt the difficulty online for each child, so that children are working at a level that is challenging but not too difficult. For instance, *Fast ForWord* is an adaptive computer-based intervention program specifically designed to improve oral language and literacy skills. Two efficacy studies conducted by the designers have shown that after a four-week intervention with the software, children with language impairments improved on measures of language skills (Merzenich et al., 1996; Tallal et al., 1996).

The first of these adaptive games developed for numeracy is *The Number Race* developed by Anna Wilson and Stanislas Dehaene (Wilson et al., 2006a; Wilson, Revkin, Cohen, Cohen & Dehaene, 2006b). Initial efficacy studies of *The Number Race* have shown encouraging results. Two previous studies have been conducted with children with developmental dyscalculia. The first was with 6-year-old children who used the software for three weeks (Räsänen, Salminen, Wilson, Aunio & Dehaene, 2009); while a second with 7-to-9-year-old children used the software for five weeks (Wilson et al., 2006b). Results showed improvements in core numeracy tasks such as number comparison and subitizing (enumeration of one to three objects), but not on calculation tasks such as addition (Wilson et al. 2006b; Räsänen, et al., 2009). A third efficacy study was conducted with 4-to-6-year-old low socioeconomic status (SES) children at risk for low numeracy (Wilson, Dehaene, Dubois, & Fayol, 2009). This study found improvement in tasks that assess number sense such as number comparison, but not on non-symbolic measures of number sense such as dot comparison.

This chapter will review relevant literature on dyscalculia, as well as discuss interventions that are currently available. It will also introduce the new version of *The Number Race* (version 3.0) and discuss preceding efficacy studies of the software.

1.2 Developmental Dyscalculia

Developmental dyscalculia, or mathematical learning disability, by which name it is known in North America, is a developmental disability in which despite average or above average intelligence and adequate instruction, children exhibit severe difficulty with the acquisition of basic number skills. As mentioned earlier, most estimates of the prevalence of

dyscalculia have been around 6% (Kosc, 1974; Shalev et al., 2000). An exception is a recent large scale study in 9-to-10-year old primary school children by Jovanović and colleagues (2013), which estimated prevalence to be 10%; however, cut-off criteria in this study was less stringent than in others. Dyscalculia is also often co-morbid with dyslexia (Badian, 1999); although research suggests that the two have separate underlying causes, at least at the cognitive level (Landerl, Fussenegger, Moll & Willburger, 2009; Wilson et al., 2014).

Children with dyscalculia usually exhibit difficulties with basic number tasks from their first year of school, although this does not mean that dyscalculia is not present earlier, but rather that it is most likely to be noticed at this age. In the first few years of primary school, children show difficulties with tasks such as counting (Geary et al., 2000; Geary et al., 1999), addition of one digit numbers (Geary et al., 2000; Geary, 1990; Geary et al., 1991), comparing numbers (Kosc, 1974; Shalev & Gross-Tsur, 1993, 2001; von Aster & Shalev, 2007) and marking the position of numbers on the number line (Geary, Hoard, Nugent & Byrd-Craven, 2008). In late primary school, difficulties become apparent in reading analogue clocks (Burny, Valcke, & Desoete, 2012), learning and recalling number facts; for example, number combinations adding up to ten or times tables (Badian, 1999; Geary, 1993; Ginsburg, 1997; Gross-Tsur, Manor & Shalev, 1996; Jordan & Montani, 1997; Ostad, 1999; Shalev & Gross-Tsur, 2001). Difficulties at such basic levels in numeracy often result in children with dyscalculia being unable to perform more complex calculations quickly and accurately (Geary, 1993).

In adulthood, dyscalculia affects basic everyday activities such as handling money (Henik et al., 2011) and understanding important numerical information (Henik et al., 2011; Stith & Fishbein, 1996). It may be for these reasons that low numeracy has been reported to

be more of a barrier to finding employment and progression within careers than low literacy (Parsons & Bynner, 1997; 2005).

1.3 Aetiology of Dyscalculia

The exact aetiology of dyscalculia remains largely unknown, although early research suggests there are both genetic and environmental roles. There is also emerging research on causes at the cognitive and neural levels.

1.3.1 Genetic Contributions to Dyscalculia

Although particular genes have not yet been identified, family and twin studies have shown that there is a strong genetic role in dyscalculia. Furthermore, dyscalculia has also been found to be associated with the cognitive profile of several genetic disorders such as Turner syndrome (e.g. Bruandet, Molko, Cohen & Dehaene, 2004) and Fragile X syndrome (e.g. Rivera, Menon, White, Glaser, & Reiss, 2002).

The first twin study was that of Alarcón, DeFries, Light and Pennington (1997), who compared mathematical performance of 63 pairs of identical and fraternal twins (one of whom had a mathematical learning disability). When verbal, performance and full-scale IQ were controlled for, the authors found that there was still a significant genetic component to the aetiology of dyscalculia. However, although this result was statistically significant, the heritability estimate (the proportion of variation in a given trait that is due to genes or the environment; ranges from 0-1) was substantially less than one. This suggests that shared environmental influences such as teaching protocols and parental support in

academics may also have a role to play. Furthermore, this study used a small sample size and mathematical disability was diagnosed based solely on school history information and a composite mathematics score on two psychometric tests. A later large-scale study by Kovas, Petrill and Plomin, (2007) which studied 1251 pairs of ten-year-old twins ($N = 2502$) showed that heritability estimates ranged from .30 to .45; while shared environmental influences (such as having the same parents and going to the same school) ranged from .08 to .30. Thus, although genetic factors do appear to play a role in dyscalculia, environmental factors (which are often shared by twins) may also influence whether dyscalculia is present in individuals.

The fact that dyscalculia is often co-morbid with other learning disabilities for which risk genes have been identified (e.g. attention-deficit hyperactivity disorder, ADHD, and dyslexia; Badian, 1999; Gross-Tsur et al., 1996) is also suggestive of a genetic role. The co-morbidities between dyscalculia and these other disorders are at a prevalence far greater than that which would be expected due to chance. For instance, the base rate of dyscalculia in the population is around 6%, but its comorbidity with dyslexia is estimated at around 60% (Badian, 1999; Lewis, Hitch & Walker, 1994). Gross-Tsur et al. (1996) found that dyscalculia is co-morbid with ADHD at approximately 30%. This research has not yet identified any genes in common between dyscalculia and the two disorders, however multivariate twin studies show that such “generalist genes” likely exist (Kovas, Harlaar, Petrill & Plomin, 2005).

1.3.2 Environmental Contributions to Dyscalculia

A number of studies have provided evidence for environmental factors that can increase the risk of dyscalculia, including low birth weight/pre-term birth and the use of psychoactive drugs (tobacco and alcohol). A study by Litt and colleagues (2012) recruited

adolescents with extremely low birth weight (< 1 kg) and compared their academic achievement, including rates of learning disabilities and special education, to that of normal birth weight controls. The authors found that adolescents with extremely low birth weight scored significantly lower on IQ tests compared to controls and also had higher rates of mathematical learning disabilities (50%) compared to their normal birth weight peers (28%).

Isaacs, Edmonds, Lucas & Gadian (2001) conducted a study of adolescents who were born pre-term at less than or equal to 30 weeks of gestation with half of the participants in this group having numerical operations difficulties; while the other half had mathematical reasoning difficulties. The authors found that adolescents who were born pre-term at thirty weeks and with low birth weight, scored significantly lower on numerical operations (23.8%) and mathematical reasoning (22.5%) tests; compared to 7% for the normative group. Pritchard et al. (2009) compared academic performance of very pre-term children (≤ 33 weeks of gestation) to children born full-term, on multiple curriculum areas. The authors found that at age six, children who were born pre-term were two to three times more likely to show delays in mathematics than children born at term (43% versus 19%), although they also showed delays in other areas. Correspondingly, they found that children born pre-term were twice as likely as children born full-term to have a mathematical learning disability (47% versus 21%). A later study by Kiechl-Kohlendorfer, Ralser, Peglow, Pehboeck-Walser & Fussenegger (2013) also found that pre-term birth (≤ 32 weeks of gestation) was associated with low numeracy. The authors found that 20% of children in their sample ($n = 27$ of 135) showed delayed numerical development at age five.

The use of psychoactive drugs such as tobacco and alcohol by expectant mothers have also been shown to be implicated in the math skills of their offspring, however, results are

somewhat contradictory. For smoking, Kiechl-Kohlendorfer (2013) also found that maternal smoking in pregnancy was predictive of delayed numeracy at age five. Another study by Piper and Corbett (2012) recruited mothers of 5-to-18-year-old children ($N = 357$) and found that children of women who smoked at least ten cigarettes per day were more likely to underperform on both math and reading compared to children who were not exposed to nicotine. Furthermore, these academic effects held regardless of maternal education levels. Not all studies have found supporting evidence, however. In a large scale quasi-experimental ($N = 654,707$) design, D'Onofrio et al. (2010) explored the relationship between smoking during pregnancy and offspring academic achievement and found that although smoking during pregnancy was statistically associated with academic achievement between unrelated individuals, full siblings who were differentially exposed to smoking during pregnancy did not differ in their academic scores. Lambe, Hultman, Torráng, MacCabe and Cnattingius (2006) found that if a mother had smoked during her first pregnancy, but not during her second pregnancy, the second child was also at risk for poor academic achievement. The reverse was also found to be true. These studies together suggest that genetics and other environmental factors may play more of a role in poor mathematical achievement.

Another environmental risk factor for dyscalculia is prenatal alcohol exposure. Kopera-Frye, Dehaene and Streissguth (1996) studied adults and adolescents with Foetal Alcohol Syndrome and (FAS) and Foetal Alcohol Effects (FAE), and found that compared to controls, they showed difficulties on calculation and estimation tests (but not with number reading and writing). However, a more recent study by O'Leary and colleagues (2013), examining the effects of prenatal alcohol exposure on academic ability in 8-to-9-year-old children did not find any effect on numeracy.

Overall, while preterm birth/low birth weight is well established as an environmental risk factor for dyscalculia, it is less clear to what extent smoking and prenatal alcohol consumption are risk factors. Further studies are needed to clarify this question.

1.4 Dyscalculia at the Cognitive and Neural Levels

A sizeable body of research has been conducted on the cognitive neuroscience of mathematical cognition (Dehaene 1997, 2001). According to the “triple-code” model of numerical cognition (Dehaene, 1992; Dehaene & Cohen, 1995), number is mentally represented in three different forms: two symbolic (visually as Arabic digits or verbally as number words) and one non-symbolic (analog magnitudes or groups of objects). Symbolic representation is thus the representation of number using linguistic symbols, such as number words and Arabic digits, whereas non-symbolic representation (or *number sense*; Dehaene, 2001) is an analogue representation of magnitude or numerosity (the number of objects in a set).

In lay person’s terms number sense can be thought of as an individual’s ability to represent and understand numbers, their magnitude and relationships, and how they are affected by arithmetical operations. Research shows that number sense is present early in infancy, that it increases in precision over childhood (Feigenson, Dehaene & Spelke, 2004; Noël, Rousselle & Mussolin, 2005), and that it is still used by adults for tasks such as the comparison of numbers, estimation, and approximate arithmetic (Dehaene et al., 2003). Contrastingly, symbolic representation is used for storage of number facts (e.g., linguistic storage of memorised addition and multiplication facts; Dehaene et al., 2003). Unlike non-

symbolic representation, children only establish symbolic representation as a result of culture and education (Rousselle & Noël, 2007; Pica, Lemer, Izard, & Dehaene, 2004).

Research has also shown that number sense has a neural basis. Neuroimaging studies in adults and children with typical numeracy achievement have found areas in the prefrontal cortex and parietal lobe that are associated with number sense; in particular the intraparietal sulcus (IPS; Cantlon, Brannon, Carter & Pelphrey, 2006; Cipolotti, Butterworth, & Denes, 1991; Dehaene & Cohen, 1997; Dehaene, Spelke, Pinel, Stanescu & Tsivkin, 1999). Cell recordings in macaque monkeys by Neider and Miller (2003; 2004) showed that some neurons in the prefrontal and parietal cortex are even specifically tuned to numerosity (the number of objects in a set). A later study by Piazza, Izard, Pinel, Le Bihan and Dehaene (2004) used an fMRI adaptation paradigm to show that in human adults the homologous region of the bilateral IPS showed the same tuning functions.

This non-symbolic representation of number, or number sense, has been shown to be associated with school mathematical achievement. For instance, Jordan, Kaplan, Locuniak and Ramineni (2007) investigated whether children's number sense at kindergarten entry predicted performance in mathematics achievement in the middle of first-grade. Results showed that children who made moderate improvements in number sense by the middle of the first year of kindergarten scored higher in mathematics than children who also started with low number sense in kindergarten but remained low, even with the inclusion of first-grade formal instruction. These results not only suggest that early number sense is a predictor of mathematical achievement in school, but also that interventions in kindergarten could help prevent difficulties with mathematics later on.

1.4.1 The ‘core deficit’ theory of dyscalculia

Given the critical role of number sense in the representation of magnitude and mathematical development, numerous authors have proposed that dyscalculia may be due to a ‘core deficit’ in number sense (Berch, 2005; Butterworth, 1999; Gersten & Chard, 1999; Gersten, Jordan & Flojo, 2005; Mazzocco, 2005, Mazzocco & Thompson, 2005; Wilson & Dehaene, 2007). Consistent with this theory, initial brain imaging findings suggest that there may be both structural and functional abnormalities in the IPS of individuals with dyscalculia. For instance, using fMRI, Kucian et al. (2006) found that compared to typically developing controls, children with dyscalculia had weaker activation in the IPS, the left inferior frontal gyrus and the right middle frontal gyrus, whilst doing a computer-generated paradigm which included a control task (grayscale discrimination task), approximate and exact calculation tasks and a magnitude comparison task. Children with dyscalculia also showed cognitive impairments in tasks involving approximate arithmetic; but not exact calculations and magnitude representations. Another fMRI study by Price, Holloway, Räsänen, Vesterinen and Ansari (2007) found that children with dyscalculia did not show the same modulation of IPS activity as did controls when performing a numerosity comparison task. Ashkenazi, Rosenberg-Lee, Tenison and Menon (2012) compared brain activity in children with dyscalculia only (no other co-morbid difficulties) to that of typically developing children whilst they performed simple and complex addition problems. The authors found that for complex addition problems, children with dyscalculia showed less activity in multiple cortical regions compared to controls, including in the IPS.

Not only have functional abnormalities been found in the IPS of individuals with dyscalculia, structural abnormalities have also been found. For example, both Rotzer et al.

(2008) and Rykhlevskaia, Uddin, Kondos and Menon. (2009) found that children with dyscalculia had less grey matter in the IPS compared to typically developing children. Other studies have found similar findings for specific populations with dyscalculia, such as genetic syndromes or individuals born pre-term. Molko et al. (2003) found that when compared to controls, individuals with dyscalculia as a result of Turner's syndrome showed less modulation of brain activity in the right IPS as a function of number size. Furthermore, the right IPS showed abnormal length, depth and sulcal geometry in this population (Molko et al., 2003). Isaacs et al. (2001) found that adolescents born pre-term who had difficulties with numerical operations (e.g. addition) had less grey matter in the left parietal lobe compared to a control group also born pre-term but without mathematical difficulties. Furthermore, the authors were unable to find any similar anomalous regions in the group of children with difficulties in a different aspect of mathematical processing (logical reasoning, which is not considered to be dependent on number sense).

Taken together, these studies suggest that abnormalities in the structure and function of the intraparietal sulcus may be a neural level cause of mathematical learning difficulties. However, their interpretation is clouded by the fact that the IPS is also known to be involved in representing space, time and movement, and also in spatial working memory (Jonides et al., 1993). For instance, a recent study by Rotzer et al. (2009), using an adaptation of the Corsi block-tapping task (a spatial working memory task), found that children with dyscalculia showed less activation in the IPS compared to typically achieving control group children, whilst doing this non-mathematical task.

Further support for the core deficit theory of dyscalculia is seen at the cognitive level when comparing magnitudes in either symbolic format or non-symbolic format (dots). For

example, Rousselle and Noël (2007) found that 7-year-old children with mathematical disabilities ($n = 45$) showed a slightly smaller *distance effect* when comparing single-digit numbers than typically developing children (the distance effect describes the finding that it takes several hundred milliseconds longer to decide which of two numbers is larger when the numerical distance between them is small, e.g., 4 versus 5, compared to when it is large, e.g., 4 versus 9. This effect is associated with activity in the IPS. On the contrary, Mussolin, Mejias and Noël (2010) also found a difference in the distance effect for 10-to-11-year-old children with dyscalculia ($n = 30$) compared to controls, however the difference was in the other direction; a greater distance effect in children with dyscalculia. This contrast in findings may be explained by a key difference in the methodology. In the Mussolin et al. (2010) study, the task presented had a 1000 msec cut-off time, while there was no cut-off time in the Rousselle and Noël (2007) study. This may have allowed the children in the latter study to employ the use of various strategies such as verbal and finger counting. Thus, introducing timed conditions in future tasks such as this may allow for more accurate effects to be found.

The comparison of numerosities (e.g. groups of dots) is known to involve the IPS and number sense; and some studies suggest that this is a difficulty in dyscalculia. For instance, Piazza et al. (2010) studied the developmental trajectory of *number acuity* (precision of internal numerosity representation). Using a dot comparison task, the researchers found that number acuity improves with age, but that 10-year-old children with dyscalculia performed at the same level as 5-year-old typically developing children. Furthermore, they also found that the severity of the number acuity impairment can predict performance on tasks which involve the manipulation of symbolic numbers.

Overall, while there is early support for the core deficit theory of dyscalculia, more evidence is needed. In particular, more brain imaging studies are needed to be sure that the IPS is indeed impaired in dyscalculia, and to establish whether these effects are specific to numerical tasks or are more general, and present because the tasks involve the use of working memory.

1.4.2 The ‘access deficit’ theory of dyscalculia

An alternative theory for the aetiology of dyscalculia, the ‘access-deficit’ theory, suggests that the deficit is not in the non-symbolic representation of quantity itself, but instead in the mapping between Arabic digits or number words and their numerical magnitudes (Rousselle & Noël, 2007). If this were the case, we would expect that tasks that measured number sense directly without passing through symbols (such as dot comparison tasks) should not show impairment, whereas those tasks which involve number symbols should show impairment.

The access-deficit hypothesis was put forward by Rousselle and Noël (2007), who compared the performance of children with mathematical disabilities to that of a control group on both symbolic number comparison of one-digit numbers and non-symbolic comparison of groups of objects. The group with dyscalculia were slower and less accurate than controls to compare symbolic numbers, but showed no difference versus controls when comparing non-symbolic quantities. A later study by De Smedt and Gilmore (2011) also supports this hypothesis. The authors compared numerical magnitude processing abilities in first-grade children with either a mathematical learning disability or low achievement in mathematics to those of typically developing children. Using a comparison task and an

approximate addition task, each presented in either symbolic or non-symbolic (dot array) formats, they found that children with either a mathematical learning disability or low achievement in mathematics showed impairment on symbolic comparison and addition, but not on non-symbolic comparison or addition.

Why have some findings supported the core deficit hypothesis, whilst others support the access deficit hypothesis? To explain this apparent contradiction, Noël and Rousselle (2011) propose that the non-symbolic impairment may only emerge in older children with dyscalculia as a result of poor links between symbolic and non-symbolic representations, which would impair tuning of the non-symbolic numerosity representation over development. However, another explanation could be the use of inconsistent populations between studies, with some including children with dyscalculia, while others use more lenient cut-off criteria, which may also include those who are low achieving in mathematics (Mazzocco, Feigenson & Halberda, 2011). Another possible explanation could be the existence of subtypes of dyscalculia, which will be discussed in the next section.

1.5 Proposed Subtypes of Dyscalculia

Mathematics requires many different cognitive components, for example number sense, verbal memory, language, logic, and spatial cognition, to name a few (Szűcs, Devine, Soltesz, Nobes & Gabriel, 2014). Even typically developing children show variability in competency across these different components. For instance, Dowker (1998) investigated the relationship between arithmetical calculation and arithmetical reasoning in 5-to-9-year-old children. Upon examination of individual data, dissociations between almost any pair of components could be found. For instance, some children showed a strong discrepancy

between calculation and derived fact strategy use, while other children showed a strong discrepancy between derived fact strategy use and arithmetical estimation.

This suggests that it should be possible to observe impairments in specific components of mathematics, or subtypes of dyscalculia. This is indeed the case in acquired dyscalculia. For example, Lemer, Dehaene, Spelke and Cohen (2003) examined two acalculic patients, one of whom had a quantity deficit, while the other had a verbal deficit. The authors found that the patient with the quantity deficit was more impaired in subtraction than in multiplication, approximation, subitizing and numerical comparison (both Arabic digits and arrays of dots), while the patient who had a verbal deficit was more impaired in multiplication than subtraction, but had intact approximation and processing of non-symbolic numerosities. In the case of developmental dyscalculia, subtype proposals have existed for more than forty years; the first being that of Kosc (1974). Several in particular have amassed a reasonable amount of evidence and still remain contenders today; these are briefly reviewed below.

Rourke and colleagues (Rourke & Finlayson, 1978; Rourke, 1993) proposed a general distinction between verbal and non-verbal learning disabilities, with the verbal subtype being associated with comorbid dyscalculia and dyslexia, and the nonverbal with dyscalculia only. Evidence for this came from the examination of cognitive profiles across neuropsychological tasks in a large clinical population. For instance, Rourke and Finlayson (1978) showed that 9-to-14-year-olds with both reading and mathematics difficulties performed well on visuo-spatial measures but poorly on verbal measures, while those with only mathematics difficulties showed the opposite dissociation. However, this early work did not always

replicate well. For instance, Share, Moffitt and Silva (1988) replicated the findings in boys only, while Shalev, Manor and Gross-Tsur (1997) could not replicate them at all.

Notwithstanding, subsequent studies continued to provide some support for verbal and non-verbal subtypes of dyscalculia. For instance, Jordan and Montani (1997) investigated problem-solving and number-fact skills in children who either had mathematics difficulties or both reading and mathematics difficulties. The researchers found that compared to controls, children with only mathematical difficulties performed worse on story and number-fact problems, but only when the tasks were timed. In contrast, the reading and mathematics difficulty group performed worse than the control group on these tasks irrespective of whether they were timed. The authors interpreted these results as suggesting that children with math difficulties only were more capable of executing verbal back-up strategies compared to children with both reading and math difficulties. In another study, Jordan and Hanich (2000) found that: a) when compared to a control group, 7-year-old children with both mathematical and reading difficulties showed more severe and pervasive difficulties in mathematics than children with only mathematical difficulties; and b) children with only mathematical difficulties outperformed children with both reading and mathematical difficulties on tasks that required reading and writing (story problems and written calculations). Finally, a study by Mammarella et al. (2013) found that compared to typically developing children, children with only mathematical difficulties showed impairment in non-symbolic tasks (dot comparison), while those with co-morbid reading and mathematics difficulties showed impairment on mental calculation and arithmetical facts.

Taken together, these studies suggest that there is a verbal subtype of dyscalculia which hinders performance on math problems requiring a significant verbal component (e.g.

story problems or fact retrieval) and that this may be predominantly present in individuals who have co-morbid dyslexia and dyscalculia.

The competing, and more popular, subtype theory is that of Geary (1993, 2004, 2010), who proposes that there are three subtypes of dyscalculia: a) a semantic memory subtype, b) a procedural subtype, and c) a spatial subtype. The first subtype is attributed to verbal memory dysfunction and is characterised by individuals having difficulties with learning and retrieving arithmetic facts both quickly and accurately. Geary suggests that this subtype is associated with dyslexia, and evidence for it is provided by many of the studies discussed above.

The second, procedural, subtype is attributed to executive dysfunction, and is manifested by a developmental delay in using simple strategies and procedures to solve arithmetic problems. A study by Temple (1991) supports the existence of a procedural subtype by demonstrating a dissociation between one child, who was able to carry out arithmetical calculations correctly, but was unable to remember number facts, and a second child, who was capable of remembering number facts but could not carry out arithmetical procedures.

Finally, the third, spatial, subtype is attributed to a dysfunction in visuospatial abilities, and is characterised by \pm sign confusion, misalignment of numbers in calculations and in areas of mathematics requiring a large spatial component, such as geometry or algebra. Geary (2010) notes that this latter subtype has the least evidence, due to a lack of research investigating spatial skills in children with dyscalculia. However it is commonly found in

adult acquired dyscalculia (Geary, 2010). In addition, a recent study by Bartelet and colleagues (2013) found a group with spatial difficulties.

1.6 Low Numeracy versus Dyscalculia

According to Geary (2011), the prevalence of children who are consistently low achieving in mathematics, but not severe enough to be classified as dyscalculia, is 10%. The less severe mathematical difficulties in this wider group may be due to low socioeconomic status (SES) or less exposure to numbers in the home environment. At the start of schooling, it can be difficult to distinguish between the two groups (Mazzocco, 2005), because it is difficult to establish whether the difficulties are ongoing and sufficiently severe for a diagnosis of dyscalculia. For this reason, many studies (including the current one) are forced to utilise samples which include children in both of these categories.

A series of recent studies have shown that the mathematical difficulties seen in those with low numeracy are qualitatively very similar to those with dyscalculia, and that the difference between these two groups seems to be mainly a quantitative one; i.e. in the degree of difficulty. One such study is that of Cowan and Powell (2014), who found that third-grade children with low achievement in mathematics did not differ when compared to children with dyscalculia on domain-general factors (working memory, reasoning, processing speed and oral language), but did differ on numerical factors that include single-digit processing efficiency and multi-digit skills such as number system knowledge and estimation.

Geary and colleagues have also found that impairments are qualitatively similar for those with low achievement in mathematics compared to those with dyscalculia. For instance,

Geary (2011) showed that children with low achievement perform similarly to those with dyscalculia on comparing numbers, retrieving number facts and solving mathematical number problems. In another study, Geary and colleagues (2008) compared the performance of two groups of kindergarten-aged children (low achievement and dyscalculia) to that of typically achieving children on a battery of number line, processing speed and working memory tasks. Low achievement children were chosen based on mathematics achievement scores below the 25th percentile, while those in the dyscalculia group were chosen based on scores below the 11th percentile. The researchers found that when compared to typically achieving children, both children with dyscalculia and low achievement performed similarly poorly when placing numbers on a number line in their first year of school. However, in their second year of school, children with low achievement performed this task more similarly to typically achieving children than did their dyscalculic counterparts. Geary and colleagues (2011) compared arithmetic fact retrieval in typically developing children to low achieving children with mild and severe fact retrieval deficits and diagnosed dyscalculia. The authors found that children with severe low numeracy performed as poorly as those with dyscalculia on fact retrieval tasks. Furthermore, when compared to children with dyscalculia, children with severe low numeracy showed less across-grade improvement over a period of four years.

Overall therefore, it appears that the mathematical difficulties of children with dyscalculia versus those of children with low achievement are different only in their degree. However, one possible fundamental difference has been identified by Geary and colleagues (2008; 2012). In the former study, it was found that when comparing children with dyscalculia to those with low achievement, those with dyscalculia showed impairment in the central executive component of working memory. In the latter study, children with dyscalculia showed impairments on all components of working memory (visuospatial sketch

pad; phonological loop and central executive). However, it is important to note that working memory difficulties may be an effect of having numeracy/arithmetic difficulties, at least when the stimuli are numerical.

1.7 Interventions

A variety of interventions have been developed to remediate or lessen the risk of mathematical difficulties. There has been a particular interest in developing interventions for young children, as they are thought to be most effective when conducted early (Gersten et al., 2005; Jordan et al., 2007). The following section will discuss three current types of mathematics interventions which have been shown to be effective: a) classroom/curriculum-based interventions; b) small-group/teacher-led interventions; and, c) computer-assisted interventions (CAIs).

1.7.1 Classroom/Curriculum-based interventions.

Classroom or curriculum-based interventions can range from the incorporation of mathematically relevant activities into the daily classroom routine, to the implementation of special programmes. An example of the former is a recent study by Piasta, Pelatti and Miller (2014) investigated the amounts and specific types of mathematical learning opportunities that were available in preschool classrooms. The researchers found that there were many opportunities to learn mathematics outside of formal instruction. One study which demonstrates this is that of Arnold and colleagues (2002). This study carried out a classroom-based intervention with 4-year-old children in two Head Start classrooms (early childhood education provided to children of low income families in the United States). The

experimental classroom teacher incorporated mathematically relevant activities into their daily routine for six weeks (e.g., into meal and circle times). Meanwhile, the control classroom teacher continued with their typical routine. When tested on standardised mathematics tests, the children in the experimental group scored significantly higher than those in the control group. Children in the experimental group were also found to enjoy math-related activities more than those in the control group. Teachers reported feeling highly satisfied with the programme and more comfortable incorporating math into daily routines.

One example of special programme implementation at the curricular level is that of Van Luit and Schopman (2000), who tested an intervention called the *Early Numeracy Programme* developed for young children with difficulties in numeracy. The programme emphasised using counting as a strategy to solve number problems. Participants included 124 five-to-seven-year-old Dutch children who were experiencing difficulties with mathematics and who attended special needs kindergartens. Half of the children ($n = 62$) received the early numeracy programme for six months, while the other half ($n = 62$) continued with the standard kindergarten curriculum. At post-test, children in the intervention group performed better on number comparison, number naming, counting, and number sense tasks. However, they did not show any evidence of transferring these gains to a novel numerical task that required strategy.

Rightstart (now called *Number Worlds*) is another curriculum-based programme for preschool or early school grade children, which emphasises basic number sense, including counting and comparing quantities, and linking number and space (Griffin, Case & Siegler, 1994). In a series of five efficacy tests over several years, at risk populations of children ($N = 98$ over all five studies) received this programme in either small groups (4-5 children per

group; 20 minutes a day) or as a whole class (20-25 children). Compared to a control group ($N = 102$ over three studies), results showed that children in both groups failed a number knowledge test at pre-intervention at similar levels, but at post-test, children in the intervention group scored significantly higher than their control group counterparts. Furthermore, there were also significant gains on transfer tests post-intervention (i.e., time-telling and money-handling). Overall, these gains allowed children who received the intervention to start first grade at a level similar to their middle-income peers and this effect was also found to hold at the end of first grade; while those that did not receive the intervention continued to underperform at the end of first grade.

1.7.2 Small-group/teacher-led interventions.

A second form of intervention that has shown promising results is that of small group or teacher-led interventions. In these interventions, children with difficulties receive special instruction either in small groups or individually from teacher aides away from the regular classroom.

One example of a small group intervention is a study conducted by Askew, Bibby and Brown (2001), who investigated the effects of an intervention in forty eight 7-to-8-year-old children with mathematical difficulties. Children worked in small groups (four per group) once a week with a teacher for 20 weeks, in which they were taught to use derived fact strategies (i.e. to use known number facts to solve unknown ones). The children who learnt the technique were able to solve three times as many number problems using derived fact strategies compared to a group of matched controls.

Another study with 9-year-olds showed encouraging results, both for small-group intervention and for individual instruction. Kaufmann, Handl and Thöny (2003) carried out an intervention with children diagnosed with developmental dyscalculia ($n = 6$), comparing their results to a normative group of children without learning disabilities ($n = 18$). Children in the intervention were taught a sequence of mathematical skills, including counting, number bonds (e.g. different combinations of numbers that make ten), place value, subtraction, addition and multiplication facts, and multistep calculations. This material was taught in a game-like or story-telling format. The intervention lasted for six months with three weekly sessions of approximately 25 minutes each. Results showed that children who received the intervention showed improvements in number sense and also in arithmetic (both fact and procedural knowledge).

Teacher-led interventions involve one-on-one individual instruction with a trained special needs teacher. The *Mathematics Recovery Programme*, was developed in Australia for 6-to-7-year-old children behind in numeracy (Wright, Martland, & Stafford, 2000; Wright et al., 2002). The intervention emphasises methods of counting and different representations of number, and typically consists of 30 minutes of individualised instruction each school day, over a period of 12 to 14 weeks. Willey, Holliday and Martland (2007) conducted a large evaluation of the programme with 210 students in the UK. Students in this programme received less than the typical intervention (20 sessions, three or four times per week). A majority of participants ($n = 197$ of 210) showed improvements in mathematics after the intervention. On average this improvement represented moving from having to see and count concrete objects in order to add two sets, to being able to work without visible objects and also to use more advanced counting strategies to solve addition and subtraction problems.

A similar programme developed in the UK, the *Numeracy Recovery Programme* (Dowker, 2001), has also showed some encouraging results. This programme is less intensive than *Mathematics Recovery*, consisting of 30 minutes of individual instruction each week for 30 weeks (around half the total time). The content emphasises the use of estimation and derived fact strategy use. In a pilot study with 6-to-7-year-old children with mathematical difficulties, showed that children who received the intervention over a six month period improved significantly on standardised arithmetic tests by an average of four points.

Overall, small group and teacher-led individualised interventions are widely used, and seem to be efficacious, however these are generally longer-term interventions, used for three to six months. Another form of intervention, computer assisted interventions, have also shown significant improvement in those with mathematical difficulties, but in a much shorter time-frame.

1.7.3 Computer-assisted interventions.

Computer-assisted interventions (CAIs) entail the use of software designed to facilitate learning in those with learning disabilities. CAIs have been utilised for over thirty years with successful results, including in preschool/kindergarten (Clements, 2002). Due to advancements in technology, such as the development of smartphones, tablets and artificial intelligence, and also increasing prevalence of computer ownership in homes and schools, the use of CAIs have increased dramatically. In particular, improvements in computing power have allowed for the development of adaptive CAIs, which use artificial intelligence to adapt to the current skill or knowledge level of each child. This ensures that each child is working at an appropriate level of difficulty most of the time.

Praet and Desoete (2014) examined whether short adaptive CAIs could be used to improve numeracy skills in 4-year-old kindergarten children ($N = 132$). Experimental children were either assigned to an adaptive CAI for counting or for number comparison. Control children continued with regular classroom instruction. The two intervention groups used their respective CAIs for nine individual sessions lasting 25 minutes each, over a period of five weeks. Results showed that children in both intervention groups significantly outperformed children in the control group in measures of arithmetic at post-test. A follow-up test the next year in first grade showed that this improvement seemed to have generalised to number knowledge and mental arithmetic. These results not only show that adaptive CAIs can be effective, but also that lasting effects can be achieved through short intervention periods.

Several adaptive computerised interventions which are broader in scope have been developed based on mathematical cognition literature, and have shown promising results in early intervention studies. For example, *Calcularis* (Käser et al., 2013) is an adaptive CAI that incorporates ten different types of games, allowing for comprehensive training in mathematical skills. These include “ordering”, in which children determine whether a sequence of numbers is presented in the correct ascending order, and “plus and minus” in which children model calculations that are presented in Arabic numerals using coloured blocks. In Käser and colleagues’ (2013) efficacy study, 8-to-9-year-old children used *Calcularis* for 20 minutes a day, five days a week, for 6-12 weeks. Half of the participants completed twelve weeks of the intervention, while the other half started after a 6-week waiting period. The inclusion of this second group allowed for the control of developmental and schooling effects. Results showed that participants improved significantly on tasks

involving number representation and arithmetic operations, with participants who received the full 12-weeks of intervention improving the most.

Graphogame-Math (Räsänen et al., 2009) is an adaptive CAI which focuses on number knowledge, using a game format. Children have to quickly choose the largest of several sets of dots which are close in numerosity (number of dots). This requires children to count and compare the exact number in each set as the dots fall from the top of the screen. As the child progresses, dot patterns advance to number symbols and then to addition/subtraction equations. An efficacy study in which *Graphogame-Math* was compared to *The Number Race* is discussed below.

1.7.4 The Number Race

The Number Race software, which is used in the current study, was the first adaptive game CAI developed for the remediation of dyscalculia and low numeracy, by Anna Wilson and Stanislas Dehaene (Wilson et al., 2006a; 2006b). It incorporates instructional principles based on cognitive neuroscience and educational findings on mathematical cognition from, for instance, strengthening both number sense and the links between the symbolic and non-symbolic representations of number, and linking number to space. An algorithm adapts the difficulty of problems presented to each child's performance, maintaining average accuracy at 75%, to ensure that each child is progressing appropriately and practising skills on which he or she requires extra training.

The Number Race intervention includes training on numerical comparison (symbolic and non-symbolic), counting, and some small addition and subtraction problems. The

intervention is delivered in a game format in which children race a character along a number line against a competitor (controlled by the computer). On each game turn, the child is required to select the larger of two quantities, both of which are less than ten, and which are simultaneously presented as groups of dots, Arabic numbers or small addition/subtraction equations. As the child progresses, timed conditions are introduced as well as traps on the number line which require the use of strategic thinking. Previous efficacy studies of *The Number Race* have shown promising results and the software has been translated into six other languages from the original French version (English, Dutch, German, Spanish, Finnish and Swedish).

The first efficacy study of *The Number Race* was conducted in nine 7-to-9-year-old children with dyscalculia (Wilson et al., 2006b), and found improved performance on core number sense tasks such as number comparison, subitizing, and subtraction, but not on other tasks such as addition. However, this study was an “open trial” only, and did not include a control group. A second efficacy study was conducted in a different population; 4-to-6-year-old kindergarten children ($N = 53$) from a low socio-economic status (SES) area (Wilson et al., 2009). This study used a two-period cross-over design where children were divided into two groups (depending on their school). Following pre-testing, one group was instructed with *The Number Race*, while the other used a commercial reading software. Children were tested again mid-study and the software used was swapped for each group and participants were tested again at the end of the study. The authors found that children improved on tasks that assess number sense such as number comparison, but did not improve on non-symbolic measures of number sense. However, because this study used a sample of children whose low numeracy was most likely due to SES, this does not speak directly to the efficacy of the software in a population with dyscalculia.

Räsänen et al. (2009) compared *The Number Race* and *Graphogame-Math*. In this study, 6-year-old children ($N = 30$) with numeracy difficulties were randomly assigned to either *The Number Race* or *Graphogame-Math*. A normative age-matched control group was also followed, but received no intervention. The intervention period lasted three weeks, during which children used the software to which they were assigned for 10-15 minutes each day at preschool. Teachers recorded time spent working with the software and rated children's motivation level. Results showed no significant improvement in counting in either intervention group but an improvement in number comparison speed in both groups, relative to the normative group. This improvement held at a three-week follow-up assessment

Taken together, these studies indicate the need to test the software in younger children during the initial period of learning number symbols and in a population with children at risk for dyscalculia. Furthermore, the software is also expected to be more beneficial at this age because interventions are thought to be more effective when conducted early (Gersten et al., 2005), and entry and primary school level mathematical skills are thought to be the best predictor of mathematics achievement throughout school (Geary, Hoard, Nugent & Bailey., 2013; Shalev, Manor & Gross-Tsur, 2005).

1.8 Summary

The importance of numeracy skills in everyday life is clearly evident in a wide variety of tasks, for instance, in handling money (Henik et al., 2011; Stith & Fishbein, 1996) and reading analogue clocks (Burny et al., 2012). However, despite the importance, little is still known about potential impediments to acquiring these skills, such as dyscalculia or mathematical learning disability. Research conducted in this area, although still lagging

behind literacy research, has shown that there may be two main contributing factors in dyscalculia: a) the ‘core deficit’ theory (eg., Dehaene et al., 2003; Wilson & Dehaene, 2007) which postulates that dyscalculia may be attributed to the impairment in the core non-symbolic representation of number, and b) the ‘access-deficit’ theory which suggests that number representations are intact but rather that dyscalculia is caused by weak connections between the non-symbolic representations of number and their symbolic counterparts. Based on these two theories, several intervention programmes have been developed.

One form of intervention which has shown promising results is adaptive computer games. These games attempt to train children in fun and interactive ways on the links between non-symbolic representations of number (i.e., dots) and their symbolic counterparts (i.e., Arabic numerals). The aims of testing these types of interventions are two-fold. Firstly, more knowledge will be discovered about the characteristics of dyscalculia/low numeracy and the developmental trajectory of mathematical knowledge, especially in young children. Secondly, it will also help to establish whether these adaptive computer games are as effective, if not more than traditional classroom/teacher-based interventions in less time and with fewer resources.

A handful of these adaptive computer games for numeracy have been developed, for instance *Calcularis* (Käser et al., 2013), *Graphogame-Math* (Räsänen et al., 2009) and *The Number Race* (Wilson et al., 2006a; 2006b; Räsänen et al., 2009) have only been tested on children in mid primary school (7-to-9-year olds). However, due to the importance of this skill, it is crucial that any impairments in acquiring this skill be addressed as early as possible, preferably from the start of primary school, in order to reduce any possible negative effects later in life. Efficacy studies which have been conducted in younger primary school

children such as *The Number Race* (Wilson et al., 2009) have only tested this software in children from low SES backgrounds who may have been experiencing low numeracy as a result of this and thus does not speak to the true efficacy of this software. Therefore, there still remains a need to test a maths-based adaptive computer game in a group of children in early primary school.

1.9 The Present Study

The aim of the current research study was to test the new version of *The Number Race* (version 3.0) which has undergone some important changes, including in instructional factors. One new instructional factor is the inclusion of “counting on”. Research by Siegler and Ramani (2008) suggests that using “counting on” in numeracy interventions might be a critical factor in building number sense, (children who can “count on” are able to recite the counting sequence starting at any number higher than one; e.g. “4....5, 6, 7”). Counting on is an important skill for children to be able to rapidly solve addition problems. In Siegler and Ramani’s (2008) study, 4-to-5-year-old children showed substantial increases in numeracy (compared to controls) after only one hour total intervention using counting on to move along squares in a board game. Another instructional factor included in the new version of *The Number Race* is the inclusion of numbers up to 40 (as opposed to 20 in previous versions), in order to scaffold early understanding of place-value. Recent studies have shown that teaching first-grade children place-value is a reliable predictor of addition performance in third-grade (Moeller, Pixner, Zuber, Kaufmann & Nuerk, 2011). These programming changes were made and distributed by colleagues in Finland (Pekka Räsänen and Alex Maslov).

As part of the current project, a new “translation” of *The Number Race* was developed using New Zealand English accents, voiced by native New Zealand English speakers. This involved sourcing and recording several hundred new sound files.

In order to test the efficacy of the new version of the software, in the current study we aimed to recruit a group of Year one and Year two (5-to-7-years-old) children with low numeracy, and implement a one-month home-based intervention, with pre and post testing using standardised mathematics achievement measures and a computerised cognitive testing battery. Due to both ethical and practical reasons, we chose not to use a matched-ability control group. However, we aimed to recruit a matched average-ability (e.g. normative) control group.

While it would be ideal to recruit a sample of children with a formal diagnosis of dyscalculia, this is currently not practicable at school entry. Current identification procedures require the use of standardised tests to establish the child is severely behind in mathematics, and that this is not due to other factors such as low IQ, or inadequate instruction. At school-entry age in New Zealand, children’s previous experience with numbers is likely to vary widely, due to a large variability in preschool instruction (for instance, not all children would have attended daycare or kindergarten). Low numeracy at this age could also be related to other risk factors such as low SES or a lack of exposure to numbers in the home environment (Mazzocco, 2005). Thus, children in this study will be described as “at risk” for dyscalculia. Some of these children may eventually be categorised as “low achieving” in mathematics.

CHAPTER TWO

METHOD

2.1 Participants

All participants for this study were recruited from two local participant schools (St. Patrick's School and St. Albans Catholic School) in Christchurch, New Zealand. Participants for the intervention group were chosen by principal and teacher recommendations. These were based on the observation of persistent and/or severe difficulties in mathematics and low scores on the Numeracy Project Assessment (an annual test administered by New Zealand schools to determine students' current numeracy level). Another criterion for recruitment was that each child also required access to a desktop computer or laptop at home to run the intervention software. Control group participants were working at an average level in mathematics and were selected by teachers and the experimenter to match the sex and age of each child in the intervention group.

Additional inclusion criteria were as follows: performance in mathematics $\leq 25^{\text{th}}$ percentile (using the KeyMaths-3; KM-3; Connolly, 2010); estimated IQ ≥ 80 (using the WPPSI-III short form and WISC-IV GAI); English as a first language; no suspected attentional difficulties; and no physical or neurological disabilities. Children with reading difficulties were not excluded because the high co-morbidity rate between mathematics and reading disabilities (40-50%; Badian, 1999) rendered this impractical.

Due to these criteria, four participants were excluded from the final sample. Two participants did not have sufficiently low performance in mathematics based on scores on the KeyMaths-3; while, another two participants did not have English as a first language as well

as attending a majority of their school years in a non-English speaking country. Therefore, the final sample for the intervention group included twelve 5-to-7-year-old children (9 girls and 3 boys) attending years 0-2 in the New Zealand school system (7 from St. Albans Catholic School and 5 from St. Patrick's School). For the control group, twelve 5-to-7-year-old children from the same schools were matched to each child in the intervention group, based on age, year level, and gender. Table 2.1 shows the means and standard deviations for age, verbal IQ, performance IQ, full IQ, numeracy project assessment scores and six year reading net for the intervention and control group and Conners-3 score for the intervention group (described further in section 2.2.4).

Table 2.1

Descriptive Statistics for Age, IQ and Conners-3 for the Intervention and Control Groups

MEASURE	INTERVENTION GROUP M (SD)	CONTROL GROUP M (SD)
Age (Years)	6.7 (0.4)	6.6 (0.1)
IQ (Verbal)	93.5 (12.5)	97.5 (12.0)
IQ (Performance)	93.7 (17.0)	93.5 (13.1)
IQ (Full)	90.5 (11.9)	94.7 (11.9)
Numeracy Project Assessment	2.8 (0.5)	3.8 (0.5)
Six Year Reading Net	6.5 (0.7)	7.3 (1.4)
Conners-3	58.8 (9.6)	-

There was no statistically significant differences between the mean age of the intervention group and the mean age of the control group, $t(11) = -0.78$, $p = 0.45$. There was also no significant main differences between the verbal IQ of the intervention group and that

of the control group, $t(11) = 1.24$, $p = 0.24$, or the performance IQ between the two groups $t(11) = 0.02$, $p = 0.98$. In addition, there was also no significant differences between the mean full IQ of the intervention group and the mean full IQ of the control group, $t(11) = -0.74$, $p = 0.47$. As expected, there were significant differences between the numeracy project assessment scores between the intervention group and the control group, $t(11) = -5.75$, $p < 0.0001$. There were no significant differences between the two groups for the six year reading net, $t(11) = -1.70$, $p = ns$.

Ethical approval for this study was obtained from the University of Canterbury Educational Research Human Ethics Committee before data collection commenced and all children and their families gave informed written consent prior to the start of the study (see Appendices A - H for information sheets and consent forms).

2.2 Materials/Apparatus

2.2.1 The Number Race.

The intervention software *The Number Race* is available for free download at: <http://www.thenumberrace.com>. The minimum system requirements are windows XP, Vista or Windows 7 with a processing speed of 1.0 GHz and 256MB of RAM. *The Number Race* is an adaptive computer game that has been designed for the remediation of dyscalculia and low numeracy. Designed by Prof. Stanislas Dehaene and Dr. Anna Wilson and validated in a series of efficacy studies (Wilson et al., 2006a; Wilson et al., 2006b), it has been shown to strengthen both number sense itself, in addition to strengthening the links between non-symbolic representations of number with their symbolic counterparts. For the purposes of this

study, the instructional factors in *The Number Race* were modified: ‘counting on’ based on the research of Siegler and Ramani (2008), was incorporated to help children improve their number sense skills, including numbers up to forty and the character voices were changed to have standard New Zealand accents. Figure A shows screenshots from *The Number Race* (version 3.0).

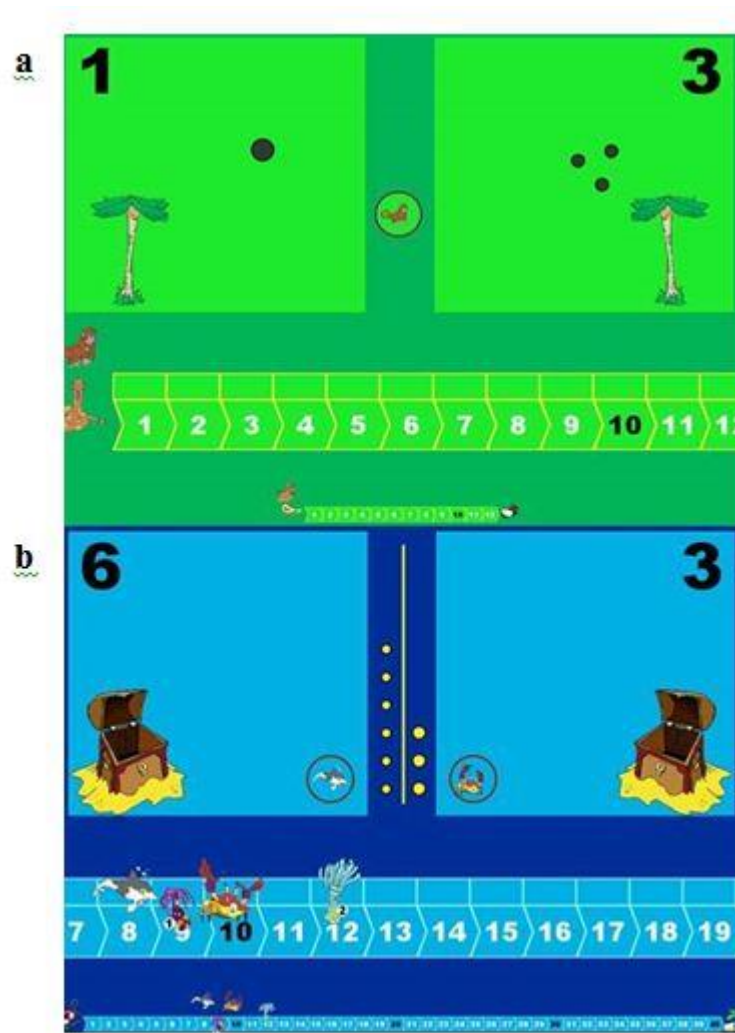


Figure 2.1. Screenshots from *The Number Race* (version 3.0). Children choose to play in one of two entertaining game worlds: in the jungle (a) or under the sea (b). In both, children choose a character to play with and have to race against a competitor character (controlled by the computer) along a number line. They have to choose the larger of two options which are presented to them in the form of dots, digits or addition and subtraction equations (numbers 1-9) (as shown in screenshot a). As the game becomes progressively harder, timed conditions and traps are introduced which require children to use strategic thinking (example of traps are shown in the screenshot b). Number lines also become longer as the game adapts to the child’s ability (the longest number line is forty). One-to-one correspondence (as shown in the screenshot b) is used to help children understand how the numbers presented relate to each

other (this is only shown once children have made a choice). Children then use these ‘tokens’ to move along the number line and the game shows equations on the screen to help children understand how they are moving along the number line. If children reach the finish line before the competitor, they win the game and are allowed to save a prisoner (fish or butterfly) which contributes towards unlocking a new character to play with.

2.2.2 Standardised Measures of IQ.

The Wechsler Preschool and Primary Scale of Intelligence 3rd edition, Australian Adaptation (WPPSI-III; Wechsler, 2002) was administered to children up to the age of 7 years 3 months, which comprised a majority of the sample ($n = 12$ experimental, $n = 11$ control). Participants older than 7 years 3 months ($n = 0$ experimental, $n = 1$ control), were tested using the Wechsler Intelligence Scale for Children 4th edition, Australian Adaptation (WISC-IV; Wechsler, 2005). A short version of each test was used, due to time constraints. Short forms are generally considered reliable for the purposes of estimating IQ for classification of learning difficulties (Sattler, 2004). The subtests used from the WPPSI-III were block design, information, matrix reasoning, symbol search, and similarities; while those used from the WISC-IV were block design, similarities, vocabulary, matrix reasoning, symbol search and information (those needed for the GAI, or Global Ability Index). The short-form IQ tests took approximately 35-45 minutes to administer.

2.2.3 Standardised Measures of Mathematics.

The KeyMaths-3 Australian Adaptation (KM-3; Connolly, 2010) was used as a diagnostic assessment of children’s mathematical achievement level. The subtests in the KM-3 can be readily linked to the New Zealand mathematics curriculum, and it is normed for years one through to thirteen. The KeyMaths-3 was used both as an inclusion test and as a

test of pre-post intervention changes. Form A was used before and after intervention, as form B was unavailable. The subtests administered were numeration, algebra, geometry, measurement, data analysis and probability, mental computation/estimation, and addition/subtraction. The KeyMaths-3 took approximately 35-45 minutes to administer.

2.2.4 Standardised Measure of Attention.

The short version of the Conners-3 (Conners, 2008) was used to assess possible Attention-Deficit/Hyperactivity Disorder (ADHD) and related issues for the intervention group. The Conners-3 is a multi-informant assessment of children and adolescents between six and eighteen years of age that takes into account home, social, and school settings. Both parent and teacher forms were used.

2.2.5 Curriculum-Based Measures.

Two curriculum-based measures were obtained from schools, the numeracy project assessment scores and the six year reading net scores. The scores from the numeracy project assessment was collected for all participants to determine how each participant was performing on measures pertaining to the New Zealand curriculum for numeracy; while, scores for the six year reading net showed each participants' current reading age.

2.2.6 Parental Questionnaire.

This 21-item questionnaire (see Appendix I) included demographic, developmental, learning and health questions.

2.2.7 Computerised Testing Battery.

The computerised battery, adapted from Wilson et al. (2006b), consisted of five computerised tests measuring different components of mathematical competence. The testing battery was designed to be fun and age-appropriate, lasted approximately 30-minutes and consisted of five tasks which each took about 5-10 minutes to complete. These tasks were designed to measure basic components of numerical cognition, and were based on work in adult neuropsychological patients with acquired dyscalculia (Lemer et al., 2003), as well as on recent work in developmental dyscalculia (Landerl, Bevan & Butterworth, 2004). The tests were programmed by Dr. Anna Wilson using E-Prime 2.0 (Schneider, Eschman, & Zuccolotto, 2002) and accuracy and reaction times were measured for all tasks. The tests were run on a Intel Core i5 2.67GHz running Windows XP laptop with a 15.6 inch screen set to 480 x 640 resolution. Children were given instructions at the beginning of each task. The experimenter sat next to the children throughout the task to ensure that they were paying attention, and also to give the children short breaks as needed. The researcher controlled the computer during the test and children responded via a key press or microphone to record manual and vocal reaction times. All stimuli details are provided in Appendix J.

2.2.7.1 Response Time.

Task one. This task measured simple manual reaction time (RT) to a visual stimulus which appeared in the centre of the screen and was included to ensure that RT improvements in other tasks were not merely due to improvements in general processing speed. Children were required to respond to a pink fish (80 pixels wide) that appeared on a black background as quickly as possible by pressing the Enter key. The computer then made a fun bubbly sound as a reward for the child's response. The stimulus remained on the screen for a total of 3000 msec, before timing out. Participants completed one block of 20 trials.

Task two. Children then completed a second block of 40 trials the same as the first, except that the fish was coloured either yellow or cyan, and they pressed one of two keys (F and J) to indicate its colour. Yellow and blue stickers were placed on the corresponding keys to help the children remember key assignments. Children were told to respond as quickly and accurately as possible. Both tasks together lasted approximately five minutes.

2.2.7.2 Dot Enumeration.

This task, based on Mandler and Shebo (1982), examined children's subitizing and counting speed by measuring vocal reaction times for enumeration of sets of one to seven dots. Previous trials with *The Number Race* showed improvements in subitizing, but not in counting. Children were asked to give the number of dots that appeared on the screen as quickly as they could, whilst trying to stay accurate, and counting if necessary. Vocal response time was measured using a microphone connected to a PST serial response box. The experimenter recorded the child's responses and also coded for any microphone errors. For

one participant, difficulty was encountered with the microphone and a back-up system was used, in which the experimenter pressed a key as soon as the child responded.

Each trial began with a central fixation symbol (a green < >) which lasted for 1000 msec. After that, a group of one to seven white dots (350 x 350 pixels) appeared on the screen. Both the fixation symbol and dots appeared against a black background. A practise trial was included in the instruction screen to ensure that participants understood the task. Participants completed 56 trials in two blocks, which took around 10 minutes to complete, with a short break in between the two blocks.

2.2.7.3 Number Comparison (symbolic task).

In this task, based on Moyer and Landauer's (1967) research, children were presented with two one-digit numbers, and were asked to indicate the larger number via a key press. Stimuli consisted of all of the possible pairs of one digit numbers (1-9, excluding zero) irrespective of order, giving a total of 32 pairs. The side on which the largest number was displayed was varied randomly from trial to trial.

Each trial began with a white fixation dot in the centre of the screen for 1000 msec, then one-digit numbers appeared on its left or right. Numbers on the left were in yellow, while the numbers on the right were in blue. Children indicated the side/colour of the larger number using the F and J keys, which was covered with stickers of the corresponding colour. All stimuli were presented against a black background. If no response was given after 3000 msec, the trial timed out. A practise trial was included in the instruction screen to ensure that participants understood the task. Children completed 32 trials in two blocks, which took approximately five minutes.

2.2.7.4 Numerosity Comparison (non-symbolic task).

In this task, children indicated which was the larger of two arrays of dots of two different numerosities. The numerosities used were -0.47, -0.29, -0.13, 0.12, 0.32, 0.49. The purpose of this task was to compare children's progress on it to that on the symbolic task. Experimental trials (shown in Figure 2.2) began with a fixation symbol (a green *), which appeared on the centre of the screen for 1500 msec. Dot arrays were presented simultaneously against a black background, with yellow dots on the left side of the screen and blue on the right. Children indicated which has more dots by pressing the F or J keys (covered with appropriately coloured stickers as in previous tasks). Stimuli remained on the screen until a response had been made (no timeout). Children completed two blocks with 48 trials in total. In between the two blocks, a short break was given.

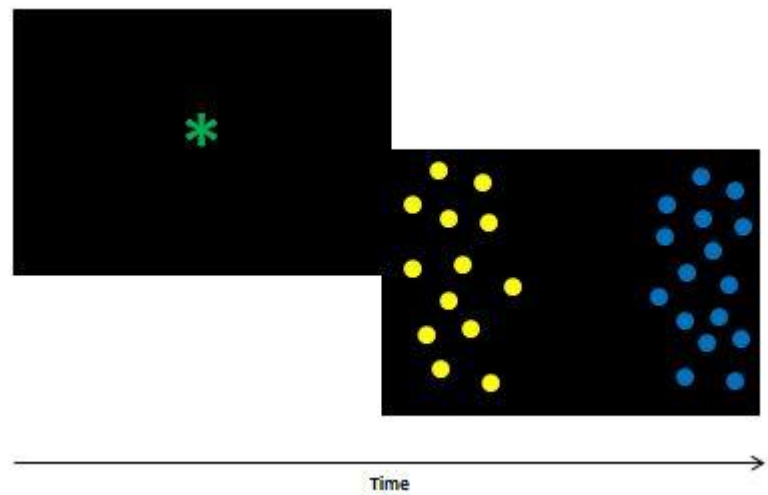


Figure 2.2. The numerosity comparison task as presented on the screen. Participants indicate whether there are more yellow dots or more blue dots.

2.2.7.5 Mental Number Line.

This task, based on research by Siegler and Booth (2004) and Siegler and Ramani (2008), was designed to investigate mappings between symbolic and non-symbolic representations of number. The task was adapted from a pencil and paper version to a computerised version (See Figure 2.3). Children were sequentially presented with 18 number lines with the endpoints of 0 and 10 marked, and asked to use the mouse to mark the position of a number from 1 to 9 on the line. Number lines were 1000 pixels long. A practise trial was included in the instructions; however, no indication was given as to whether the child placed the number correctly in this practise trial. There were 18 trials in two blocks and all numbers and number lines were presented in black against a white background. The task took approximately five minutes in total.

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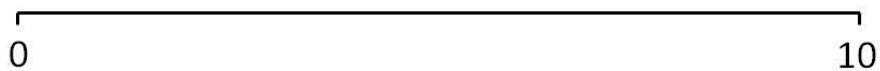


Figure 2.3. The mental number line task as presented on the screen. Using the mouse, children indicate where the number presented at the top of the screen (e.g., four) would be placed on the number line.

2.3 Procedure

The study took place over a period of three months and consisted of four phases: screening, pre-testing, intervention, and post-testing.

The first stage of the study, eligibility screening, began after principals and teachers had given permission for the study and had recommended students for participation. Children were screened for IQ, attention difficulties (experimental group only), and mathematical achievement level. The children were screened individually by a female examiner in a quiet room at their school. After each test or subtest, children were given a short break, and allowed to select a sticker to put on a completion certificate. IQ and mathematics measures were administered in two separate testing sessions. The main mathematical achievement test used (KeyMaths-3) also doubled as a pre-testing measure. In addition, in the pre-testing phase, all children in the intervention group completed numeracy profiling tests that were more comprehensive using a computerised test battery, in a separate testing session. Curriculum-based measures (the numeracy project assessment scores and six year reading net) were also collected from schools for all participants at this stage.

The intervention phase took place in the children's homes, under parental supervision. Each child played *The Number Race* five days a week for approximately twenty minutes each day, for a period of one month. Once installed on each child's home computer, the experimenters explained the software to the parents, who were then asked to keep a record of the amount of time their child spent each day on the intervention (recorded on a homework log designed for this study). Parents were also asked to check that their child remained on task, and to keep sessions as close to twenty minutes as possible. During the intervention phase, the experimenter visited each child and family in their homes at the two-week point and also at the end of the intervention. During these visits, the experimenter checked on progress with *The Number Race* and encouraged the children to continue. This was incentivised by offering a toy of the child's choice as a reward for having completed the homework log at the end of the month. During weeks one and three, when the experimenter

did not visit the homes, phone calls were made to each family instead to check on each child's progress.

The post-intervention tests were administered following the same procedure as in the screening and pre-testing phases. Intervention group children were tested in two sessions: firstly, the KeyMaths-3 and secondly, with the computerised testing battery. While, control group children had only one testing session with the KeyMaths-3. In addition, during this period, a questionnaire was given to the parents of each child in the intervention group in order to gather information about their child's learning, development and health (parental questionnaire as described in section 2.2.6).

CHAPTER THREE

RESULTS

In this chapter, results from the standardised mathematics test (KeyMaths-3) and the computerised testing battery are presented. Analyses were conducted using Microsoft Excel, SPSS, and GraphPad. The distributions for all variables were inspected for normality, with major outliers being removed if necessary.

3.1 KeyMaths-3

Results for each subscale of the KeyMaths-3 are presented, followed by the results from each subtest. The differences between pre-test (T1) and post-test (T2) raw scores for each group were analysed using a series of 2 x 2 (group x time) repeated-measures ANOVAs. Although analysing standard rather than raw scores would have been preferable, standard scores were not available for the *Mental Computation and Estimation* subtest for the youngest participants in the study (years 0-1). Therefore, raw scores were analysed instead. Table 3.1 presents the means and standard deviations for the variables tested in the KeyMaths-3 for both the intervention and control groups.

3.1.1 Basic Concepts Subscale and Subtest Results.

The *Basic Concepts* subscale comprises of five subtests: (a) *Numeration*, (b) *Algebra*; (c) *Geometry*; (d) *Measurement*; and (e) *Data Analysis and Probability*. Analyses for the Basic Concepts subscale showed a significant main effect of group, with the control group

scores being significantly higher on average than those for the intervention group, (48.6 versus 37.5, respectively; $F(1,11) = 6.65, p = 0.03$). There was no significant main effect of time ($F(1,11) = 0.65, p = ns$), and no significant interaction effect ($F(1,11) = 0.89, p = ns$). Therefore, there was no evidence for either group showing improvement across time for these scores, nor for a differential pattern of improvement in one group versus the other. Even disregarding statistical significance, the results were not in the direction expected, with the intervention group showing a slight decrease of around half a point. The control group showed only a small non-significant improvement of around three points, $t(11) = -0.97, p = ns$.

Numeration. The numeration subtest also showed a significant main effect of group ($F(1,11) = 7.84, p = 0.02$) with the control group scores being higher than the intervention group scores on average. There was no significant main effect of time ($F(1,11) = 1.87, p = ns$), which in any case showed a trend in the opposite direction to that hypothesised, with both the intervention and control group scores unexpectedly decreasing from T1 to T2. There was no significant interaction effect ($F(1,11) = 0.05, p = ns$).

Algebra. Results for the algebra subtest again showed a significant main effect of group, with control group scores higher on average than the intervention group scores ($F(1,11) = 7.26, p = 0.02$). No significant main effect of time was found ($F(1,11) = 1.67, p = ns$). There was a marginally significant interaction effect, driven by an improvement in the control group scores between T1 and T2, while the intervention group scores remained the same ($F(1,11) = 3.75, p = 0.08$).

Geometry. The ANOVA for geometry yield no significant effects. There was no significant main effect of group ($F(1,11) = 0.71, p = ns$), of time ($F(1,11) = 0.07, p = ns$) and no significant interaction effect ($F(1,11) = 0.26, p = ns$).

Measurement. For the measurement subtest, there was a significant main effect of group, with the control group scores being significantly higher on average than the scores for the intervention group ($F(1,11) = 5.30, p = 0.04$). There was also a significant main effect of time, with average scores increasing slightly between T1 and T2 ($F(1,11) = 5.39, p = 0.04$). This increase appears to have been mostly driven by the control group, although the interaction effect was not significant ($F(1,11) = 1.57, p = ns$).

Data Analysis and Probability. A significant main effect of group was found, with the control group scores higher on average than those of the intervention group ($F(1,11) = 9.44, p = 0.01$). Although both groups showed a small increase in scores between T1 and T2, there was no significant main effect of time ($F(1,11) = 0.77, p = ns$). There was also no significant interaction effect ($F(1,11) = 0.44, p = ns$).

3.1.2 Operations Subscale and Subtest Results.

The Operations Subscale consists of two subtests: (a) *Mental Computation and Estimation*; and (b) *Addition/Subtraction*. Analyses for the operations subscale showed a significant main effect of group, with the control group having higher scores on average than the intervention group (12.8 versus 8.4, respectively; $F(1,11) = 7.69, p = 0.02$). As with the previous subscale, there was no significant main effect of time, ($F(1,11) = 0.73, p = ns$). However, unlike with the previous subscale, the interaction effect was marginally significant

($F(1,11) = 3.79, p = 0.08$), and this was in the hypothesised direction. The intervention group showed a marginal increase in scores from T1 to T2 (7.6 to 9.2, respectively), $t(11) = -1.83, p = 0.10$, whereas the control group showed a slight non-significant decrease in scores over the same time (13.1 to 12.5), $t(11) = 0.79, p = ns$. Although this interaction was only marginal, a further t -test showed no significant difference between the intervention group and control group at T2 ($t(11) = -1.76, p = ns$), providing some evidence that using *The Number Race* resulted in an increase in childrens' computational skills.

Mental Computation and Estimation. The mental computation and estimation subtest showed a marginally significant main effect of group, with the control group scoring slightly higher than the intervention group on average, ($F(1,11) = 4.09, p = 0.07$). There was no significant main effect of time ($F(1,11) = 0.02, p = ns$). There was also no significant interaction effect, ($F(1,11) = 1.54, p = ns$), although the scores for the intervention group increased between T1 and T2, while the scores for the control group decreased.

Addition/Subtraction. The addition/subtraction subtest showed a significant main effect of group as on average the control group participants scored higher than the intervention group participants ($F(1,11) = 11.65, p < 0.01$). There was no significant main effect of time ($F(1,11) = 0.98, p = ns$). No significant interaction effect was found, ($F(1,11) = 1.71, p = ns$), even though the intervention groups' score increased between T1 and T2, while the control group scores remained stable between T1 and T2

Table 3.1

Means Scores on the KeyMaths-3 for the Intervention and Control Group, by Subscale/Subtest, and Timepoint.

MEASURE	<u>INTERVENTION GROUP</u>		<u>CONTROL GROUP</u>	
	Time 1 M (SD)	Time 2 M (SD)	Time 1 M (SD)	Time 2 M (SD)
BASIC CONCEPTS	37.7 (10.5)	37.3 (9.2)	47.2 (14.2)	50.0 (16.3)
Numeration	8.6 (2.4)	8.0 (2.5)	11.3 (3.7)	10.4 (4.4)
Algebra	4.3 (1.9)	4.3 (1.5)	5.8 (2.7)	7.0 (3.0)
Geometry	11.3 (2.9)	11.2 (2.7)	12.0 (3.4)	12.3 (3.0)
Measurement	7.1 (2.9)	7.2 (3.2)	9.2 (2.9)	10.3 (3.8)
Data Analysis and Probability	6.4 (3.3)	6.7 (2.0)	8.9 (3.3)	9.9 (4.0)
OPERATIONS	7.6 (2.8)	9.2 (2.8)	13.1 (4.7)	12.5 (6.1)
Mental Computation and Estimation	4.0 (1.7)	4.4 (1.2)	6.3 (3.0)	5.9 (2.9)
Addition/Subtraction	3.6 (2.5)	4.8 (2.1)	6.8 (2.3)	6.6 (3.5)

Note: Basic Concepts and Operations are subscales with their subtests listed below.

3.2 Computerised Testing Battery

This section presents the results from the computerised testing battery, which comprised of five tests: (a) *Response Time (Simple Response Task and Choice Response Task)*; (b) *Dot Enumeration (Subitizing Range and Counting Range)*; (c) *Number Comparison (symbolic task)*; (d) *Numerosity Comparison (non-symbolic task)*; and (e) *Number Line*. These tasks were administered to the intervention group only. Unless indicated otherwise, both reaction time and accuracy were analysed, using ANOVAs and *t*-tests. Median reaction times were calculated for each participant for correct responses only. The median was used as opposed to the means in order to reduce the effect of possible outliers.

3.2.1 Response Time.

3.2.1.1 Simple Response Task.

1. Reaction time for the simple response task.

To compare whether there were any significant differences in reaction time between T1 and T2 in the simple response task, a paired-samples *t*-test was conducted. Results showed that there were no significant differences between reaction time at T1 ($M = 473$ msec, $SD = 117$ msec) and T2 ($M = 438$ msec, $SD = 79$ msec); $t(11) = 1.20, p = ns$.

2. Accuracy for the simple response task.

Although this task required only a response without any choice, accuracy on a given trial was recorded as zero if there was no response within 10 seconds. A paired-sample *t*-test for accuracy revealed no statistically significant difference between accuracy at T1 ($M = 98\%$, $SD = 4\%$) and T2 ($M = 100\%$, $SD = 0\%$), $t(11) = -1.30, p = ns$.

3.2.1.2 Choice Response Task.

1. Reaction time for the choice response task.

For the version of this task in which a simple choice was required, a paired-samples *t*-test showed that there was no significant difference between the response time at T1 ($M = 814$ msec, $SD = 140$ msec) and the response time at T2 ($M = 786$ msec, $SD = 165$ msec), $t(11) = 1.15$, $p = ns$.

2. Accuracy for the choice response task.

As expected, accuracy levels decreased slightly when a choice needed to be made. A paired-samples *t*-test showed that there was no significant difference in accuracy between T1 ($M = 91\%$, $SD = 5\%$) and T2 ($M = 92\%$, $SD = 4\%$), $t(11) = -0.82$, $p = ns$.

This lack of a significant difference for the response time tasks overall was the expected result, and confirms that any differences found in reaction time for other tasks cannot be due merely to a general improvement in response time from T1 to T2.

3.2.2 Dot Enumeration (Subitizing Range).

1. Verbal response time for the subitizing range.

The subitizing range includes numerosities one to three. Following Landerl et al. (2004) and Wilson et al. (2006b), these numerosities were analysed separately from the counting range (numerosities four to seven). For the purposes of this analysis and also for the

counting range analysis, one participant was removed due to microphone failure (and therefore a lack of verbal response time data), and one further participant was removed due to an outlying median reaction time (> 1100 msec). However, both participants' data were included for the accuracy analyses. Table 3.2 presents the means and standard deviations for each numerosity, while Figure 3.1 shows mean group reaction times for the subitizing range at T1 and T2.

Table 3.2

Group Means for Individual Median Reaction Time in the Subitizing Range, by Numerosity and Timepoint.

Numerosity	<i>n</i>	Time 1 M (SD) msec	Time 2 M (SD) msec
1	10	996 (154)	778 (57)
2	10	1084 (243)	827 (127)
3	10	1347 (293)	1012 (176)

A 2 x 3 (time x numerosity) within-subjects ANOVA was carried out to determine whether there were any significant differences in the subitizing range between T1 and T2. Results showed a significant main effect of numerosity ($F(2,18) = 30.66, p < 0.0001$), and visual inspection of Figure 3.1 suggests that the intervention childrens' subitizing range was on average closer to two than to three. A significant main effect of time ($F(1,9) = 21.36, p = 0.001$) shows that intervention children became significantly faster at subitizing after using *The Number Race*. No significant interaction effect was found ($F(2,18) = 2.08, p = ns$), suggesting that while overall response time for subitizing increased, the range of subitizing remained the same.

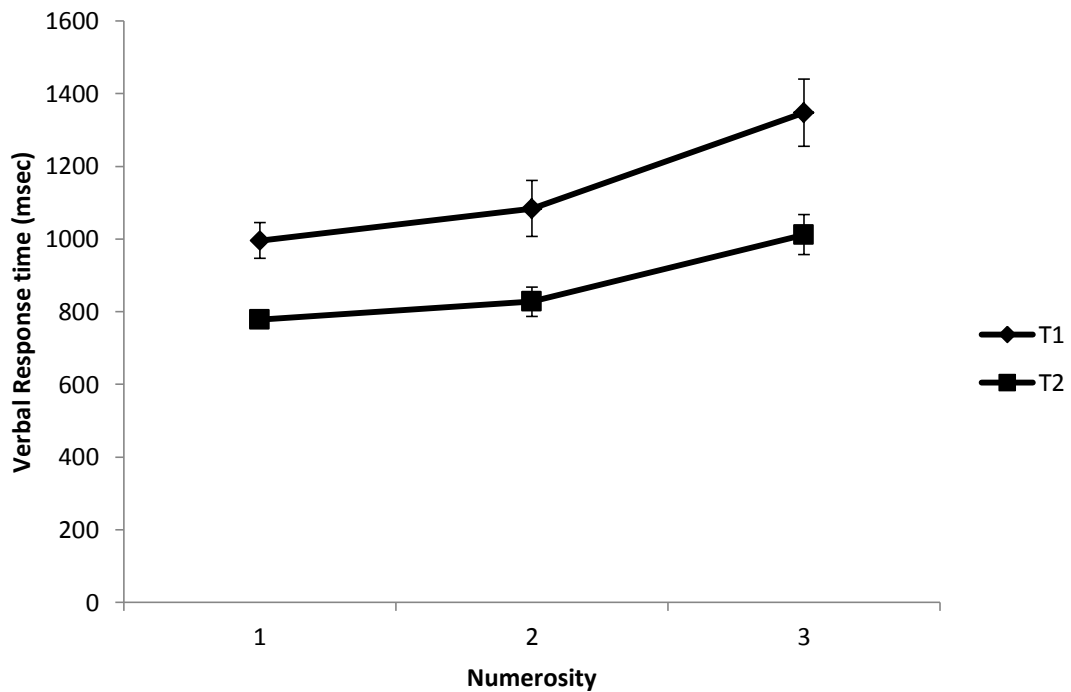


Figure 3.1. Mean verbal response time for the subitizing range, by numerosity and timepoint. Error bars represent one standard error.

To confirm the interpretation of the subitizing range described above, a series of post-hoc *t*-tests were conducted. At T1, response time to enumerate one object was not significantly different to that for two objects, $t(9) = -1.69$, $p = ns$. This was also the case at T2, $t(9) = -1.73$, $p = ns$. However, enumerating three objects was significantly slower than two objects at both T1 and T2 ($t(9) = -3.94$, $p = 0.003$; $t(9) = -4.73$, $p = 0.001$, respectively). These results confirm that the main effect of numerosity reflects a reduced subitizing range in the intervention group.

2. Accuracy for the subitizing range.

A 2 x 3 (time x numerosity) within-subjects ANOVA with the accuracy data for the subitizing range revealed no significant main effects, likely because accuracy was largely at ceiling. There were no significant main effects for time ($F(1,11)=1.00$, $p = ns$), numerosity

($F(2,22)=1.00$, $p = ns$), nor any significant interaction effect ($F(2,22)=1.00$, $p = ns$). Table 3.3 shows the means and standard deviations of accuracy levels for each numerosity in the subitizing range.

Table 3.3

Mean Accuracy in the Subitizing Range, by Numerosity and Timepoint.

Numerosity	<i>n</i>	Time 1 M (SD) %	Time 2 (SD) %
1	10	100 (0)	100 (0)
2	10	100 (0)	100 (0)
3	10	99 (3)	100 (0)

3.2.3. Dot Enumeration (Counting Range).

1. Reaction time for the counting range.

The counting range includes numerosities four to seven. Table 3.4 presents the means and standard deviations for both T1 and T2.

Table 3.4

Mean Reaction Times for the Counting Range, by Numerosity and Timepoint.

Numerosity	<i>n</i>	Time 1 M (SD) msec	Time 2 M (SD) msec
4	11	2666 (656)	2357 (485)
5	11	3144 (558)	2806 (603)
6	10	3581 (944)	3084 (462)
7	10	4146 (766)	3901 (629)

Results from a 2 x 4 (time x numerosity) within-subjects ANOVA showed a statistically significant main effect of time ($F(1,9) = 14.89, p = 0.004$), with intervention participants showing faster counting at T2 compared to T1, by around 350 msec. There was also a significant main effect of numerosity ($F(3,27) = 32.24, p < 0.0001$), which was of course expected in the counting range, as it reflects the counting process. There was no significant interaction effect ($F(3,27) = 0.27, p = ns$). Figure 3.2 shows the mean group reaction time for each numerosity in the counting range for T1 and T2.

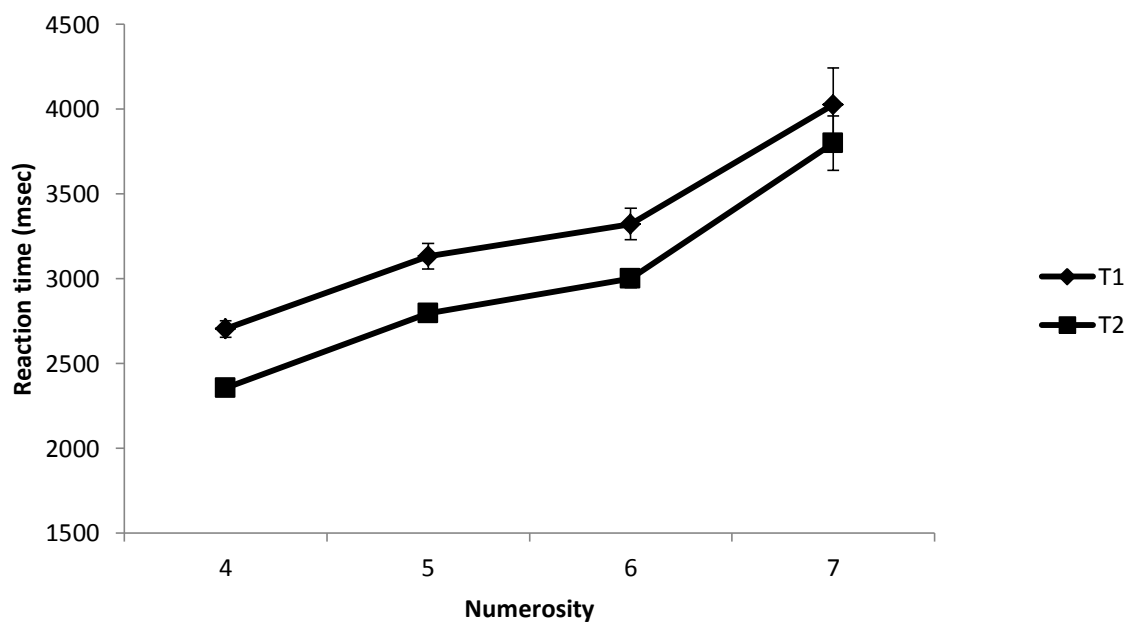


Figure 3.2. Mean reaction time for the counting range, by numerosity and timepoint. Error bars represent one standard error.

2. Accuracy for the counting range

Table 3.5 presents mean accuracy for each numerosity in the counting range. A 2 x 4 (time x numerosity) within-subjects ANOVA for accuracy at each timepoint revealed that there was there was a significant main effect of numerosity, ($F(3,33) = 6.82, p = 0.001$), with

accuracy decreasing as numerosity increased. This finding is consistent with previous results in older children (Landerl et al., 2004) . Although participants were slightly less accurate at T2, this difference was not significant, i.e. there was no significant main effect of time, ($F(1,11) = 0.95, p = ns$). There were no significant interaction effects, ($F(3,33) = 1.30, p = ns$).

Table 3.5

Mean Accuracy for the Counting Range, by Numerosity and Timepoint.

Numerosity	<i>n</i>	Time 1 M (SD) %	Time 2 M (SD) %
4	11	98 (4)	88 (14)
5	11	89 (11)	85 (10)
6	10	82 (24)	83 (26)
7	10	74 (30)	68 (28)

Figure 3.3 shows the accuracy levels for each numerosity in the counting range for T1 and T2.

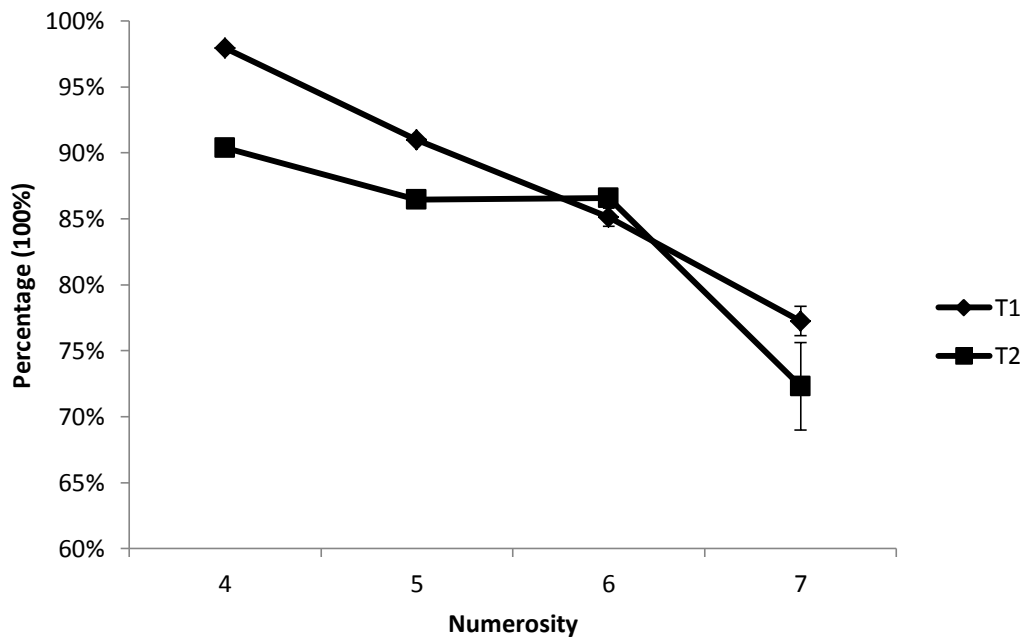


Figure 3.3. Mean accuracy for the counting range, by numerosity and timepoint. Error bars represent one standard error.

Given that participants showed faster counting at T2 than T1, but were slightly less accurate (even though the latter difference was not significant), the precaution of analysing inverse efficiency (Reaction Time/Accuracy) was taken, in order to rule out the possibility of a speed-accuracy trade-off. A 2 x 4 ANOVA (time x numerosity) was conducted for inverse efficiency. This still revealed a significant main effect of numerosity ($F(3,30) = 16.40, p < 0.001$), confirming that this effect in the previous analyses could not be explained merely by speed-accuracy trade-offs. There was no significant main effect of time ($F(1,10) = 0.21, p = ns$), nor any significant interaction effect, ($F(3,30) = 0.08, p = ns$). Figure 3.4 shows inverse efficiency for the counting range in the enumeration task.

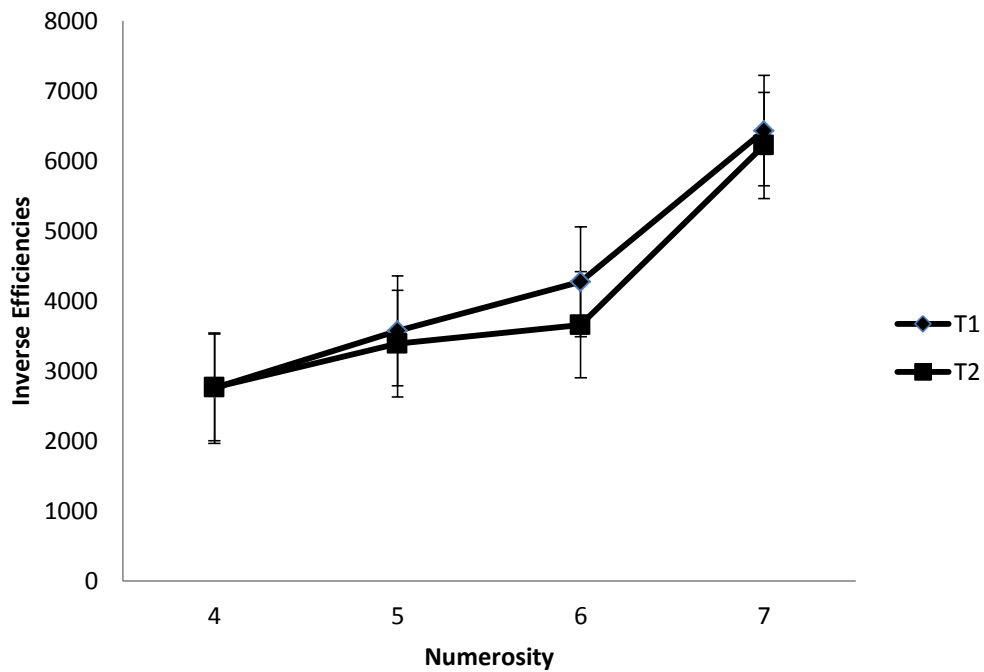


Figure 3.4. Inverse efficiencies for the enumeration task (counting range) at T1 and T2. Error bars represent one standard error.

3.2.4 Number Comparison (Symbolic Task).

1. Reaction time for the number comparison task.

The number comparison task was analysed by time and ratio. The closer the two numbers are numerically, the smaller the ratio. Table 3.6 presents the means and standard deviations for reaction times; while Figure 3.5 shows reaction times in graph format. In order to group stimuli for analysis, ratio values were binned into ratio categories, and an average value for each stimulus group was calculated. One participant was removed from analysis due to outlying reaction times (> 2000 msec on multiple variables), but was included for the accuracy analyses.

Table 3.6

Mean Reaction Time for the Number Comparison Task, by Ratio and Timepoint.

Average ratio	<i>n</i>	Time 1 M (SD) msec	Time 2 M (SD) msec
0.2	11	1715 (353)	1549 (292)
0.46	11	1665 (406)	1438 (288)
0.79	11	1533 (286)	1339 (235)
1.45	11	1436 (271)	1215 (199)

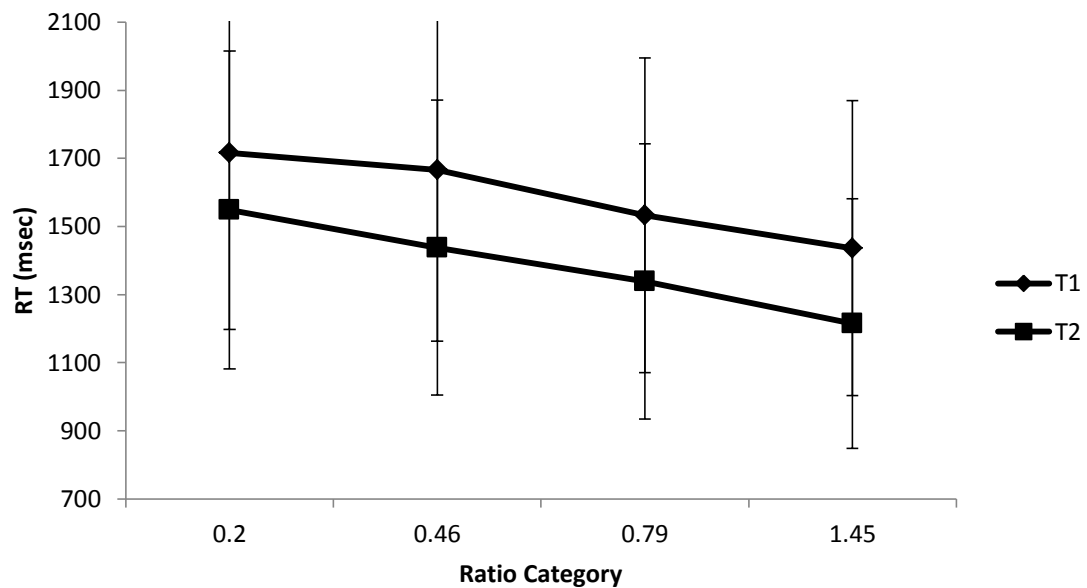


Figure 3.5. Mean reaction time for number comparison, by ratio and timepoint. Error bars represent one standard error.

Although the data in Table 3.6 suggests that participants became faster at T2 compared to T1, a 2 x 4 (time x ratio) within-subjects ANOVA showed that there was no significant main effect of time ($F(1,10) = 3.33, p = ns$). There was the expected significant main effect of ratio category ($F(3,30) = 9.49, p < 0.001$), reflecting the well-established

distance effect (the closer in magnitude numbers are, the longer it takes to make a comparison response) (Sekuler & Mierkiewicz, 1977). No significant interaction effect was found, ($F(3,30) = 0.09, p = ns$). Overall then, the reaction time data did not show any effect of intervention.

2. Accuracy for the number comparison task.

Accuracy data for number comparison is presented in Table 3.7.

Table 3.7

Mean Accuracy for Number Comparison, by Ratio and Timepoint

Average ratio	<i>n</i>	Time 1 M (SD) %	Time 2 M (SD) %
0.2	12	73 (19)	82 (13)
0.46	12	84 (11)	90 (13)
0.79	12	89 (13)	93 (8)
1.45	12	92 (11)	96 (8)

Figure 3.6 shows the accuracy levels at T1 and T2 for each ratio category. Consistent with an improvement due to use of *The Number Race*, accuracy improved between T1 and T2. As expected, accuracy levels decreased when the two numbers presented were closer in magnitude (the *distance effect*). These observations were confirmed by a 2 x 4 within-subjects ANOVA (time x ratio) which revealed that there was both a significant main effect of time ($F(1,11) = 4.99, p < 0.05$) and ratio category ($F(3,33) = 11.02, p < 0.001$). There was no significant interaction effect, ($F(3,33) = 0.21, p = ns$).

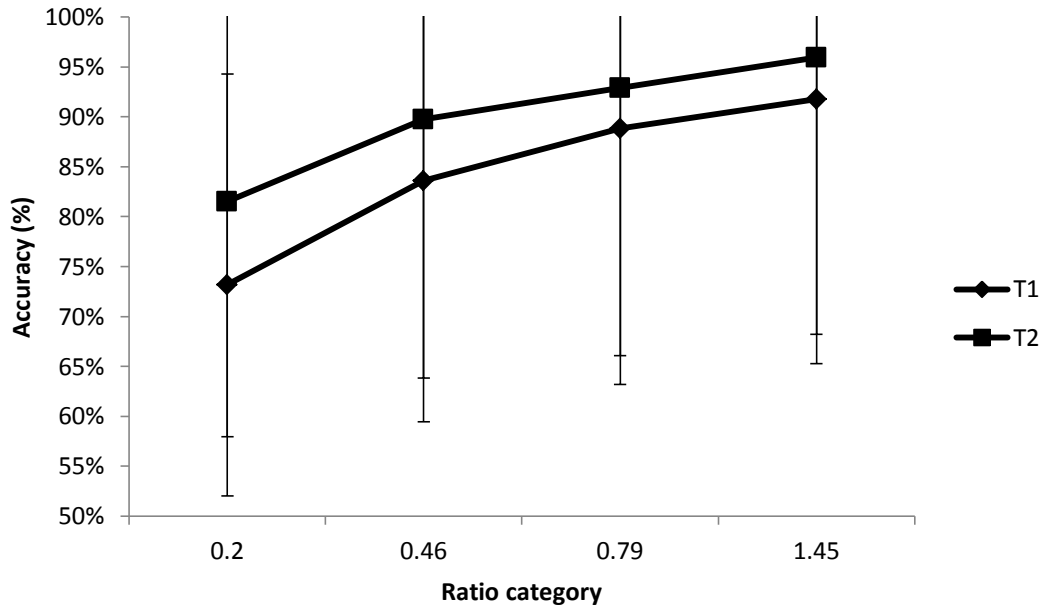


Figure 3.6. Mean accuracy for number comparison, by ratio and timepoint. Error bars represent one standard error.

3.2.5 Numerosity Comparison (Non-Symbolic Task).

Accuracy scores for numerosity comparison were analysed following the procedure used in Piazza et al. (2004). The width of each participants' internal weber fraction (w) was estimated using GraphPad software to run an iterative nonlinear curve fitting procedure (Levenberg-Marquardt algorithm). This procedure fit two free parameters (δ and w) to the following model:

$$P_{different}(n_1, n_2) = 1 - \frac{1}{2} \left(\operatorname{erf} \left(\frac{\delta+x}{\sqrt{2}w} \right) + \operatorname{erf} \left(\frac{\delta-x}{\sqrt{2}w} \right) \right), \text{ where } x = \ln \left(\frac{n_1}{n_2} \right)$$

This equation calculates the probability of a “different” judgment given two numerosities (n_1 and n_2), as a function of their log ratio (x). The parameters fitted represent

each participant's internal decision criterion (δ) and their precision of internal numerosity representation (w).

Unfortunately, however, this analysis did not proceed as planned, because there were three participants for whom the algorithm did not converge on a solution at either T1 or T2. Additionally, there were four participants for whom the average fit (R^2) was less than 0.2 at T1 or T2. For the remaining five participants, curves could be fit (examples shown in Figure 3.7), a group analysis with such a small n was obviously inappropriate.

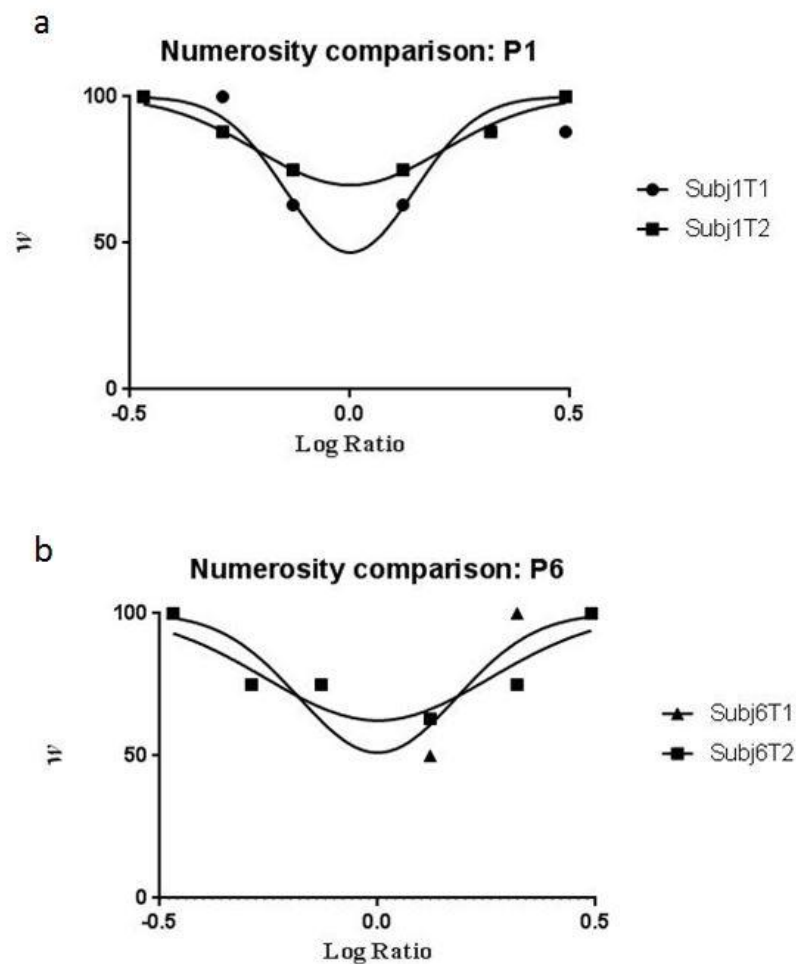


Figure 3.7. Individual curve fitting results for the numerosity comparison task for two participants.

3.2.6 Mental Number Line.

Figure 3.8 shows number line placement data for the intervention group. On the x axis is the number given to the participants, whilst the y axis represents the position that was marked on the number line. If children's mental number line is linear, then the data would approximate a straight line (indicated by the dashed diagonal). Previous research by Siegler and Booth (2004) and Booth and Siegler (2006) found that children in the first year of school tended to show a logarithmic response pattern, but that this pattern becomes linear in the first few years of schooling. However, it is clear from visual inspection that data in the current study were neither linear nor logarithmic, but instead showed more of an exponential pattern.

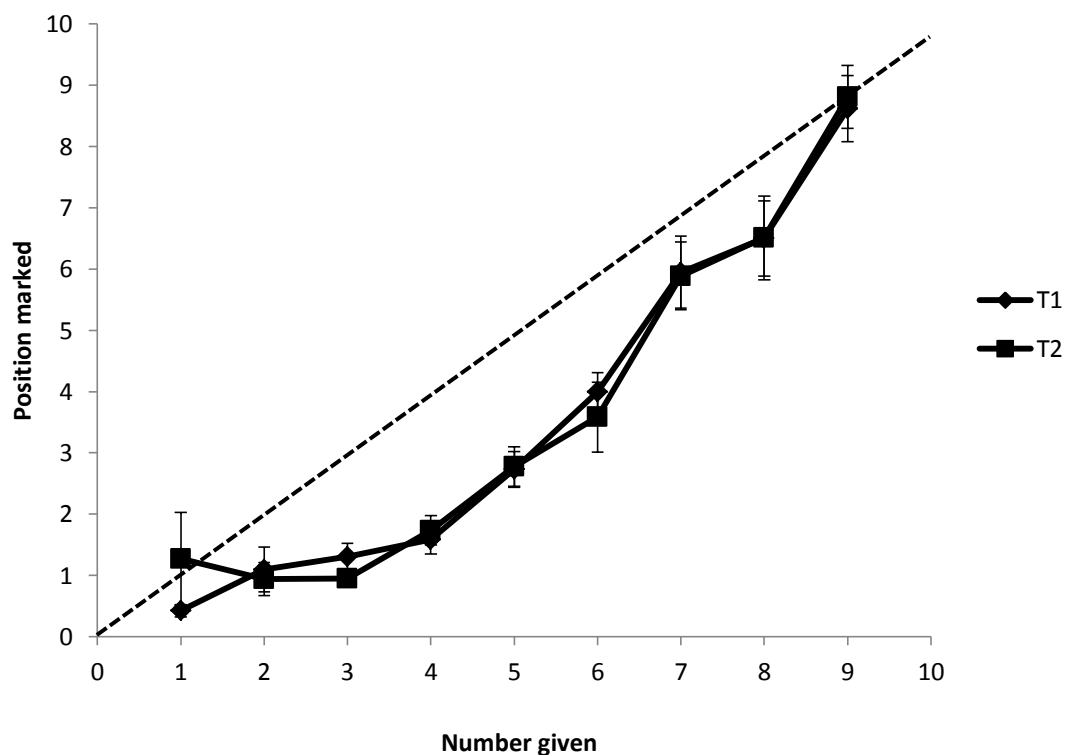


Figure 3.8. Mean position marked by children for each number given in the mental number line task, at T1 and T2. Error bars represent one standard error.

Notwithstanding, traditional analyses were initially carried out, and linear fit (R^2) and the slope of the best fitting line was calculated for each participant for both T1 and T2. To

determine whether there was any significant difference between the two timepoints, two *t*-tests were conducted, one for the slope of best fitting line, and the second for linear fit. Neither of these were significant ($t(11) = 1.34, p = ns$; $t(11) = 1.54, p = ns$; respectively).

Dehaene (2001) argued that internal representation of quantity is logarithmic in nature, and initial research by Siegler and colleagues using the number line task supported this theory and also suggested the task was a good measure of children's internal representation (Siegler & Booth, 2004; Booth & Siegler, 2006). However, a recent study by White and Szűcs (2012) suggests that childrens' performance on this task might be more variable and strategic than anticipated. They found that the youngest children (mean age 6.4 years) may have primarily used the left most point of the number line as an anchor, instead of using both extremes; while slightly older children may have employed strategies such as using both extremes, which resulted in more accurate positions being marked on the number line. A second conclusion of the authors was that younger children may be less capable than older children of using the half-way mark between the two extremes to refine their judgements.

In the current study, observation of children during the number line task suggested they may have been using strategies such as counting, even though efforts were made during the testing period to discourage this. In order to further investigate whether this could have been an issue in the current data, participants' individual graphs were inspected. Consistent with the recent findings of White and Szűcs (2012), a wide range of patterns were seen. Some children's responses showed a clear linear pattern and some an exponential pattern, but still others showed patterns consistent use of counting and/or anchoring as strategies. Figure 3.9 presents several individual graphs from participants in the present study.

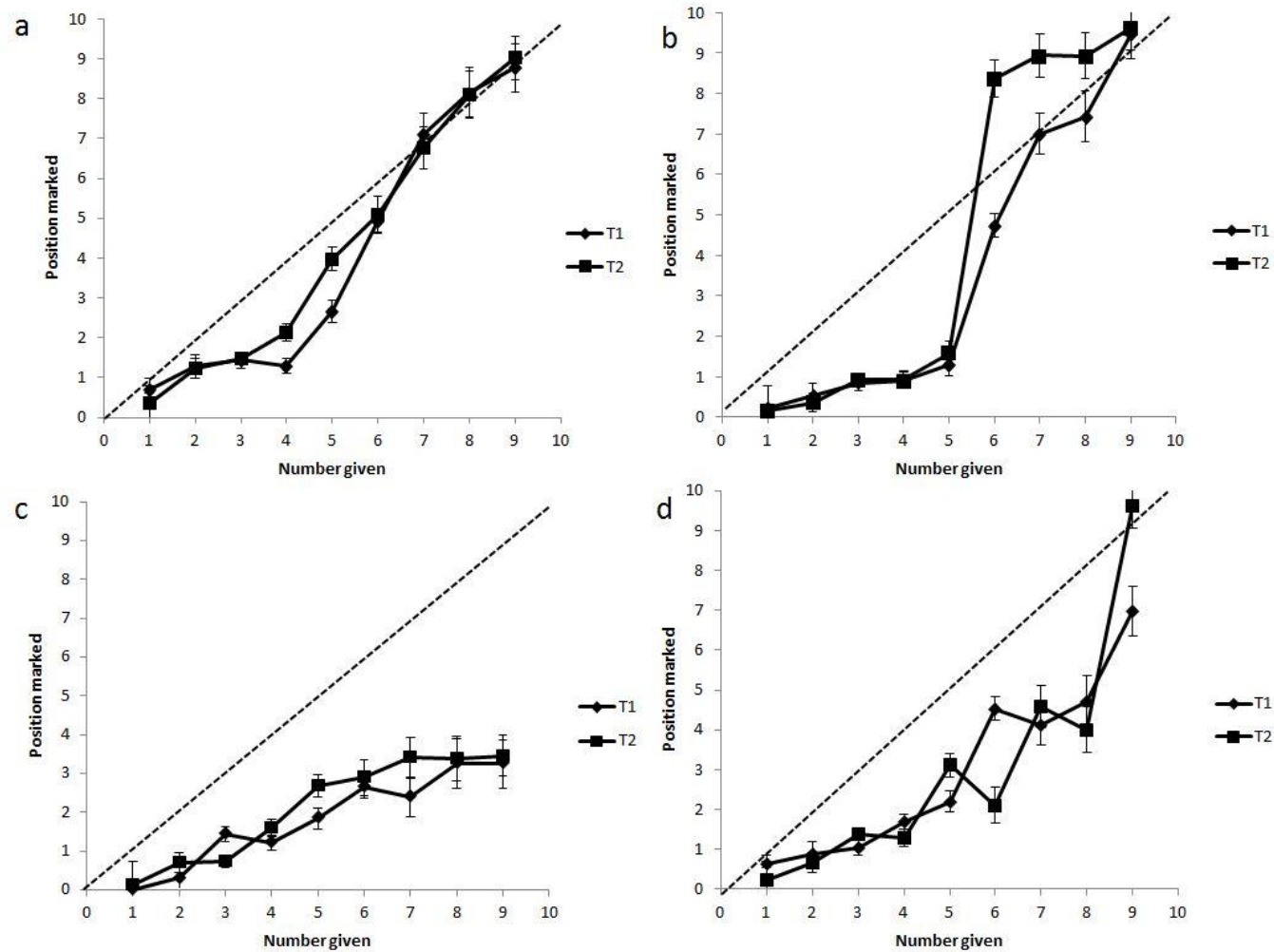


Figure 3.9. Selected individual graphs from the number line task. Participant 8 (a) shows a linear number line, however Participant 16 (b) shows evidence of using the endpoints of the line as anchors to count forwards or backwards. Participant 2 (c) also seems to be using a counting strategy, but only from the left end of the line, while Participant 7 (d) shows an exponential pattern.

CHAPTER FOUR

DISCUSSION

The present study tested the efficacy of a new version of adaptive software for mathematics remediation called *The Number Race*, using twelve 5-to-7-year old children with low numeracy, and an typical ability control group matched on age and sex. A one-month home-based intervention with the software was used, and efficacy was measured with standardised tests and a computerised battery.

4.1 Overall Findings

The KeyMaths-3 standardised test was used to measure whether there was an intervention effect of *The Number Race* in children with low numeracy, compared to typically achieving control children who recieved no intervention. An intervention effect was expected, given that the test is a good measure of numeracy, including those particular aspects instructed by *The Number Race* (number comparison, estimation, counting and simple addition and subtraction), and has been used in developmental studies of numeracy (Mazzocco & Thompson, 2005).

Results from the KeyMaths-3 showed some intervention effects, although these were more limited than hoped. There was a marginally significant intervention effect for the operations subscale (which included mental calculation and estimation, as well as pencil and paper addition and subtraction). However, the basic concepts subscale, as well as its subtests of numeration, algebra, geometry, measurement, and data analysis/probability showed no intervention effect; there was little to no improvement seen in scores for the intervention

group from T1 to T2, and there was no interaction with the control group. It is worth noting, however, that there was little change from T1 to T2 for even the control group on this subscale. This lack of measurable improvement suggests that perhaps the basic concepts subscale of the KeyMaths-3 had insufficient sensitivity for measuring change over the short time period of the study. Likewise, stronger results might have been obtained with the Operations subscale over a longer period of time. Other research studies which have used the KeyMaths have tended to be developmental and typically retest at yearly or half-yearly intervals (Mazzocco & Thompson, 2005). The computerised testing battery, which was only used within the intervention group, showed stronger intervention effects. It is firstly important to note that childrens' performance on the response time task showed no difference between pre and post-testing, confirming that improvements seen in subsequent tasks were not due to general improvements in processing or response speed.

When enumerating one to three objects, participants showed a smaller subitizing range than expected (two instead of three) based on previous literature (Landerl et al., 2004; Wilson et al., 2006b). Although this range did not change over the course of the study, at T2 children became significantly faster overall at subitizing. The same results were also found in previous efficacy tests of *The Number Race* (Räsänen et al., 2009; Wilson et al., 2006b).

Various studies have shown that children with dyscalculia face difficulties with basic numerical skills, such as counting (Geary et al., 1999; 2000) and number comparison (Kosc, 1974; Shalev & Gross-Tsur, 1993, 2001; von Aster & Shalev, 2007). It was anticipated that with use of *The Number Race* children would improve in these skills. Following the one-month intervention, children in the current study also showed a significant improvement in counting speed between T1 and T2. This effect was not found in previous efficacy studies of *The Number Race* (Räsänen et al., 2009; Wilson et al., 2006b; Wilson et al., 2009). Although

participants also became less accurate, post-hoc analyses of inverse efficiency ruled out speed-accuracy trade-off as an explanation of the improvement in speed. This improvement in counting may have been due to the inclusion of ‘counting on’ in the new version of *The Number Race*.

When comparing two one-digit numbers (number comparison; symbolic task), children were no faster at T2 than T1, however they were significantly more accurate. This finding fits with those from previous efficacy studies of *The Number Race* (Wilson et al., 2006b; Räsänen et al., 2009), although in the previous study which used a similar computerised task, the effect was seen in reaction time, rather than accuracy. Children in the current study were on average two years younger than those in Wilson et al. (2006b), and younger children tend to show less accuracy on number comparison (Sekuler & Mierkiewicz, 1977). This might explain why in the current study the effect was seen in accuracy.

The mental number line task also showed some unexpected, but interesting, findings. It was expected that children would show a logarithmic pattern to their responses, as in Booth and Siegler’s (2006) original work. However, initial analyses of the current results showed no significant differences between T1 and T2 for linear fit (R^2) and the slope of best fitting line. On further inspection, children’s responses showed a wide range of patterns such as exponential, linear and even no pattern at all. These findings were more consistent with a later study conducted by White and Szűcs (2012) who found that 6-to-8-year-old children showed a variety of response patterns and may have used multiple strategies such as relying on the left most point of the number line (the zero) as an anchor whilst ignoring both the other extreme and the half-way mark.

For the numerosity comparison task (non-symbolic task), a group analysis was unable to be conducted due to a lack of clean data for curve fitting. Therefore, comparisons were unable to be made to previous studies of *The Number Race*, which also included a numerosity comparison task (Wilson et al., 2006b; 2009).

Overall, results were consistent with previous efficacy studies of *The Number Race* (Räsänen et al., 2009; Wilson et al., 2006b; Wilson et al., 2009), and provide further (modest) evidence for efficacy of the software. Use of *The Number Race* was associated with increases in subitizing and counting speed, as well as increased accuracy in numerical comparison. Children also showed a marginally significant improvement in mental computation and estimation, as well as addition and subtraction on standardised testing.

4.2 Limitations and Future Directions

The most important limitation of the study was that the computerised testing battery, which showed the strongest results, was only administered to children in the intervention group. This was a necessity due to practical constraints (a lack of time and testing personnel). However, it had been expected that there would be stronger changes in the standardised test (KeyMaths-3), and that the computerised battery would then primarily serve to break down the exact nature of these changes. Unfortunately, however, the KeyMaths-3 did not show results as strong as expected. In this situation, because there was no control group for the computerised battery, we cannot be sure that effects seen in this task were definitely due to the software, and not to test-retest improvements, or classroom instruction.

In future studies, therefore, it would be best to administer the computerised testing battery to all children, regardless of group. Inclusion of this step would also be able to help give support to tasks from other studies that have shown that, when compared to typically developing children, children with dyscalculia face difficulties with tasks such as counting (Geary et al., 1999; 2000), comparing numbers (Kosc, 1974; Shalev & Gross-Tsur, 1993, 2001; von Aster & Shalev, 2007) and placement on number lines (Geary, Hoard, Nugent & Byrd-Craven, 2008). An added benefit of this might allow for a more comprehensive analysis for tasks that showed considerable response variability, such as the numerosity comparison and mental number line tasks. A comparison of variability between the intervention and control groups could shed light on the development of these tasks in both children who are typically achieving and those with low numeracy. Unrelated to the question of the software efficacy, the finding that there were various response strategies on the number line supported previous findings by White and Szűcs (2012), and provided a possible interesting path for future investigation.

The second most important limitation of the current study is that follow-up measures were not collected. As *The Number Race* trains core skills underlying numeracy, it is possible that larger benefits are seen over time than immediately after software use. Collection of follow-up measures was originally planned for the current study, using NumPA (Numeracy Project) data on childrens' maths performance, which is collected by teachers at the beginning of each academic year. Unfortunately however, due to a misunderstanding about the nature of this data, it ended up being unsuitable for analysis. In future studies, a full follow-up administration several months later of the measures used at pre and post-testing would be ideal. However this was outside the scope of the current project.

This present study was the first study using *The Number Race* in which participants completed the intervention at home under parental supervision. Although this made the study more feasible from a practical point of view, it meant that the intervention was not as controlled as in previous studies. Parents were encouraged to ensure that session times were kept as close to twenty minutes each school day as possible. Inspection of homework logs kept by parents suggested that there was some variability in intervention fidelity. For instance, although most children completed the twenty minutes required each day, two children spent almost twice as long as their peers on the software. Some participants failed to complete sessions each weekday, and then “caught up” over the weekend. Both of these factors may have increased variability in intervention efficacy across children. Future studies of this software should consider either how to mitigate these issues, or else employ controlled administration of the software by researchers or teachers in classroom or pull-out settings. If a home-based intervention is required, future studies could utilise a similar method to that used by Käser et al. (2013) in an intervention study using the *Calcularis* software; although these researchers used a home-based intervention, they also had mandatory in-laboratory sessions with the software.

Establishing the optimal intervention period for *The Number Race* (and also how this might vary with age and extent of numeracy difficulties) would also be useful for future studies. Previous studies have used a variety of intervention lengths. Wilson et al. (2006b) administered the software for thirty minutes, four days a week for five weeks; while Wilson et al. (2009) only administered a total of six sessions of twenty minutes each. In Räsänen et al. (2009), children used *The Number Race* each weekday for 10-15 minutes over a period of three weeks. This present study required participants to play the software five days a week for four weeks. The use of ABA (applied behaviour analysis) methodology might be one way to establish this with the minimum use of resources.

Due to ethical reasons, a matched ability control group was not used in the current study. However, using a control group that was already in the average range for numeracy is of course a limitation as the control group baseline scores were already significantly higher than those of the intervention group. Future studies with more time and personnel resources could utilise a wait-list design. For example in a recent test of the intervention software *Calcularis* (Käser et al., 2013), the authors had two groups of similar ability complete the intervention, with half receiving the intervention throughout the study, and the second half beginning after a waiting period. Thus, during the waiting period, this second group would serve as an ability-matched control group for the first.

Several aspects of the sample could have contributed to limitations of the current study. Firstly, once participants who did not meet inclusion criteria (plus their matches in the control group) were removed ($n = 4$ for each group), the sample size was reduced to $n = 12$ for each group, thus reducing statistical power. Future studies would benefit from working with larger schools, where it would be possible to recruit a larger number of eligible participants.

Secondly, recruiting participants from two schools and multiple classrooms, each of which had their own teacher, may have been a limitation. While this allowed for as many participants as possible to be recruited, it also reduced sample homogeneity by adding in variance in mathematics instruction between teachers and between schools. Although New Zealand schools follow a standard curriculum, teachers' individual instruction methods vary, and different schools use different textbooks and instructional materials. Recruiting participants from a larger school would help reduce between-school variation, however given that class sizes are limited by national mandate, between-teacher variation could still not be avoided. Another factor contributing to variance might be the cumulative effects of between-

teacher instructional difference over the course of the year. This might be able to be reduced by starting a study in the first half of the year, unlike the current study, which was conducted in the second half of the year.

Thirdly, this study was conducted in children who were already at school age. Preschool and kindergarten instruction in New Zealand varies considerably, and attendance is not compulsory, nor is it usual for all children to attend full-time. Therefore some children may have been more school-ready than their peers, and children would likely have had variable early numeracy skills. Future studies of *The Number Race* could address this by testing the software in kindergarten children (e.g. 4-year-olds) who are only starting to learn the links between non-symbolic number representations and their symbolic counterparts. Conducting an intervention with children this age might have the added benefits of increasing school readiness, and reducing anxiety towards mathematics. The main stumbling block for this future direction, however, is that it is difficult to identify children with low numeracy prior to formal schooling. A previous efficacy study of *The Number Race* (Wilson et al., 2009) was carried out with 4-year-old children from a low SES population; however it is currently unclear to what extent low numeracy associated with low SES is similar to the low numeracy which is a precursor of dyscalculia

Further analyses may be conducted with the data already obtained from this present study. For instance, a non-curve fitting analysis could be done on the numerosity comparison tasks such as those done in previous studies of *The Number Race* (Wilson et al., 2006b). In addition, more elaborate dissection of the parent questionnaire may have alluded to other factors that may have confounded our results or could lead to further lines of research. For example, as the parental questionnaire included questions such as each child's birth weight, parental involvement in their child's learning and other family members that may have a

learning disability. Being able to explore this data more fully may lead to some interesting findings about our sample. Future studies may consider obtaining this information from parents of both groups as this questionnaire was only given to parents of the intervention children. If this data was obtained, it may be more likely to be able to find correlates between environmental factors such as birth weight and parental involvement to achievement in school. This data (in addition to data obtained from the numeracy project assessment scores and six year reading net) may also be able to help uncover whether possible subtypes were also present in our sample. In particular, knowing whether children had both reading and mathematical difficulties or mathematical difficulties only would have been able to shed light on whether there is indeed a verbal and non-verbal subtype of dyscalculia (Jordan & Hanich, 2000; Jordan & Montani, 1997; Mammarella et al., 2013; Rourke, 1993; Rourke & Finlayson, 1978).

Overall, this present study has helped to identify potential features, such as ‘counting on’, that may be beneficial for the development of future CAIs. Furthermore, it has also shed some light on how mental number lines are represented in young children.

4.3 Conclusions

The current study aimed to test the efficacy of an updated version of an adaptive software called *The Number Race* (version 3.0) which was designed for the remediation of dyscalculia and low numeracy. Consistent with previous findings, children showed improvements in both subitizing and comparison of one-digit numbers. In addition, they also showed an increase in counting speed. Standardised testing revealed marginally significant improvement in mental computation and estimation as well as addition/subtraction. Despite

some methodological limitations, the current study still contributes to literature supporting modest efficacy for *The Number Race*.

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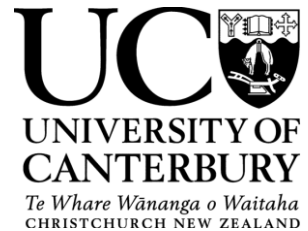
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APPENDIX A

Parent Information Sheet (Intervention Group)

Department of Psychology
University of Canterbury
Private Bag 4800
Christchurch



Boosting numeracy using "The Number Race" **Information sheet for parents / guardians**

Dear parent / guardian,

I am a sixth year Psychology student carrying out research as part of my Master's degree. My project is investigating the use of an educational computer game to improve numeracy.

I would like to invite you and your child to participate in this research. Your child has been selected because his / her numeracy scores are lower than average. Participation would first involve testing your child at school for an hour to see how he/she is doing in maths, reading, attention and general intellectual ability.

If eligible, your child will be asked to play an interactive computer game called "The Number Race" for 20 minutes five times a week, for a month. "The Number Race" helps to teach and practice numeracy, and is fun and easy to play. It does not require your supervision other than just checking your child stays on-task. I would come to your house to install the software, and also a couple of times over the month to check how things are going. On the first visit I would also interview you for 15 minutes about your child's learning and development.

As well as this I would need to give your child an hour of tests at school both prior to and following using the software. These tests are to measure progress in numeracy, and are entertaining for children.

Finally I would also need your permission to obtain a copy of the numeracy and literacy achievement information on your child that your school has for this year, and also at the beginning of 2013. This is so we can look at the long term benefit of the software for your child.

Participation in this study requires you to have access to a PC computer or laptop with internet access. Minimum system requirements are: Operating system XP, Vista or Windows 7, processing speed 1.0 GHz, RAM 256 MB.

Participation in this research is completely voluntary. If you decide to participate, you have the right to withdraw from the study at any time without penalty. If you withdraw we will do our best to remove any information relating to you or your child, providing this is practically achievable.

All information collected throughout the study will be available only to myself and researchers working on this project (this includes my supervisor and her students) The confidentiality and anonymity of you and your child will be assured by using numbers instead of names, and all information will be stored in a locked office or filing cabinet, or in password protected electronic form. The data from this project will be destroyed after five years.

There is a small risk that doing the tests in the study could make your child feel anxious. If this occurs we will stop testing, and discuss this with your child and yourself before deciding whether to continue. There is also a risk that the tests at the beginning of the study might suggest that your child could have learning difficulties (e.g. reading, attention or general intellectual ability). If this does occur, we will give you advice about following this up.

The results collected from your child will be used in conjunction with data from other participants to answer my research questions. These results will be reported as part of my Master's Thesis which will be submitted to the University of Canterbury as a piece of academic work to be marked. A copy of my thesis will be made available to the university library and could potentially be published in academic journals. None of these reports will identify yourself or your child.

A copy of the finished study or a report on the findings can be made available to you on request. You can choose whether or not you would like your child's results to be available to the school.

I encourage you to make contact with myself or my supervisor Dr. Anna Wilson if you have questions about the study at any stage.

This study has been granted ethical approval by the University of Canterbury Educational Research Human Ethics Committee and any complaints should be addressed to The Chair, Educational Research Human Ethics Committee, University of Canterbury, Private Bag 4800, Christchurch or human-ethics@canterbury.ac.nz.

If you are interested in participating in this study, please complete the enclosed consent form and return it in the prepaid envelope provided. Alternatively you can email me a scanned copy (address below).

Sincerely,

Patricia Kant

Patricia Kant

Email: patricia.kant@pg.canterbury.ac.nz

Ph: 03 389-0129 home, or

022 161 5572 mobile

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APPENDIX B

Child Information Sheet (Intervention Group)

Department of Psychology
University of Canterbury
Private Bag 4800
Christchurch



Boosting numeracy using "The Number Race" Information sheet for children

Hello!

I'm Patricia and I'm doing a project at my school for grown ups. If you and your parents say it's ok, I'd like to help you learn about numbers.

This is what we would do. First of all, at school I would give you some fun tests to do.

Then I would come to visit you at your place, and put a game on your computer. The game is fun, and it will help you with numbers. Your job would be to play the game! Your parents would get you to play the game every school day for 20 minutes, for a month. I would come and visit you a couple of times to see how you're doing.

After a month, at school I'll give you the tests to do again, and I will tell your parents how you do.

I will also tell your teacher how you do if your parents say that's ok.

You will be given a secret code name so that no-one will know how you do in the tests and the game, except us. We will keep the code name in a safe place.

If you ever get worried about anything, you can tell me or your parents. You can always change your mind about doing this and no one will be upset with you. All you have to do is to tell your parents or me.

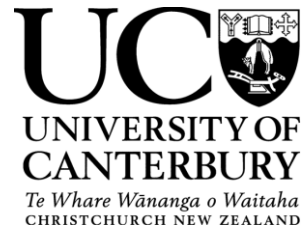
I hope you would like to help with my project!

Patricia

APPENDIX C

Parent Consent Form (Intervention Group)

Department of Psychology
University of Canterbury
Private Bag 4800
Christchurch



Boosting numeracy using "The Number Race" Consent Form for Parents and Guardians

I have been given a full explanation of this research project and an opportunity to ask questions.

I understand what will be required of me and my child if I agree to take part in this project.

I understand that my child's school will provide my child's numeracy and literacy achievement data for 2012 and 2013 to the researchers as part of the project.

I understand that my participation is voluntary and that I or my child may choose to withdraw at any stage without penalty. If I do so, the researchers will do their best to remove any information relating to me and my child.

I understand that any information provided by myself, my child, and my child's school will be kept confidential to the researchers involved with the project and that any published or reported results will not identify me or my child.

I understand that all data collected for this study will be kept in locked and secure facilities and/or in password protected electronic form, and will be destroyed after five years.

I understand that there is a small risk that the tests in the study might make my child feel anxious, or suggest the presence of learning difficulties, and that if this occurs the researchers will discuss this with me.

I understand that if I require further information, or that if I would like a copy of the findings of the study, I can contact either Patricia Kant, or her supervisor, Dr Anna Wilson.

If I have any complaints I can contact the Chair of the University of Canterbury Educational Research Human Ethics Committee.

By signing below I agree for my child to participate in this research project.

Name: _____ Date: _____

Signature: _____

Email address: _____ Phone: _____

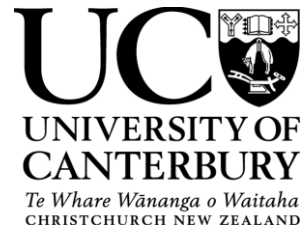
I am happy for my child's results to be given to his/her school ☐ Yes ☐
No

**PLEASE RETURN THIS SIGNED FORM IN THE PRE-PAID ENVELOPE
PROVIDED**

APPENDIX D

Child Consent Form (Intervention Group)

Department of Psychology
University of Canterbury
Private Bag 4800
Christchurch



Boosting numeracy using "The Number Race" Consent Form for Children

My mum or dad has told me about your project.

I am happy for you to help me learn about numbers.

I understand that this means that:

- First I will do some tests with you at school.
- Then you will come to our house and give me a computer game about numbers.
- I will play this game for 20 minutes on school days, for a month.
- Then you will do some more tests with me at school.
- I know that you won't tell anyone else about how I do, except my parents (and also my teacher if my parents say that's ok).
- I understand that the things you find out about me will be kept safe.

I know that if anything makes me feel worried, I can tell you or my parents about it.

I understand that I can always change my mind about doing all this and no-one will mind.

I know that if I have any questions I can ask you or my parents.

Child's name: _____

Signed by child (or on behalf of child): _____

Date: _____

APPENDIX E

Parent Information Sheet (Control Group)

Department of Psychology
University of Canterbury
Private Bag 4800
Christchurch



Boosting numeracy using "The Number Race" Information sheet for parents / guardians

Dear parent / guardian,

I am a sixth year Psychology student carrying out research as part of my Master's degree. My project is investigating the use of educational software to improve numeracy in children who are behind in this area.

I would like to ask for permission for your child to participate in this research as a "control" or comparison participant. **Your child has been selected because his/her numeracy scores are in the average range.** Being a comparison participant means that we would measure your child's progress in numeracy, and that we would average that with the progress of other children in the comparison group. We would then compare that average to the average progress made by the children who are using our software, to see if they have caught up with their classmates.

Participation would involve us testing your child at school for an hour at the start of term and again at the end of term to measure the progress he/she has made in maths, as well as his/her general intellectual ability.

I would also like your permission to obtain a copy of the numeracy and literacy achievement information on your child that your school has for this year, and also at the beginning of 2013. This is so we can compare progress in numeracy in the two groups over a longer time period.

Participation in this research is completely voluntary. If you decide to participate, you have the right to withdraw from the study at any time without penalty. If you withdraw we will do our best to remove any information relating to you or your child, providing this is practically achievable.

All information collected throughout the study will be available only to myself and researchers working on this project (this includes my supervisor and her students). The confidentiality and anonymity of you and your child will be assured by using numbers instead of names, and all information will be stored in a locked office or filing cabinet, or in password protected electronic form. The data from this project will be destroyed after five years.

There is a small risk that doing the tests in the study could make your child feel anxious. If this occurs we will stop testing, and discuss this with your child and yourself before deciding whether to continue.

The results collected from your child will be used in conjunction with data from other participants to answer my research questions. These results will be reported as part of my Master's Thesis which will be submitted to the University of Canterbury as a piece of academic work to be marked. A copy of my thesis will be made available to the university library and could potentially be published in academic journals. None of these reports will identify yourself or your child.

A copy of the finished study or a report on the findings can be made available to you on request. You can choose whether or not you would like your child's results to be available to the school.

I encourage you to make contact with myself or my supervisor Dr. Anna Wilson if you have questions about the study at any stage.

This study has been granted ethical approval by the University of Canterbury Educational Research Human Ethics Committee and any complaints should be addressed to The Chair, Educational Research Human Ethics Committee, University of Canterbury, Private Bag 4800, Christchurch or human-ethics@canterbury.ac.nz.

I have included an information sheet about the study for your child, for you to go through with him/ her. If you and your child are interested in participating in this study, please complete the enclosed consent forms and return them to your child's teacher.

Sincerely,

Patricia Kant

Patricia Kant

Email: patricia.kant@pg.canterbury.ac.nz

Ph: 03 389-0129 home, or

022 161 5572 mobile

Research Supervisor

Dr Anna Wilson

College of Education

University of Canterbury

Private Bag 4800

Christchurch 8140

Email: anna.wilson@canterbury.ac.nz

Ph: 03 364-2987 x44107

APPENDIX F

Child Information Sheet (Control Group)

Department of Psychology
University of Canterbury
Private Bag 4800
Christchurch



Boosting numeracy using "The Number Race" **Information sheet for children**

Hello!

I'm Patricia and I'm doing a project at my school for grown ups.

If you and your parents say it's ok, I'd like to do some fun tests with you at school.

At the end of the term I'll give you the tests to do again, and I will tell your parents how you do.

I will also tell your teacher how you do if your parents say that's ok.

You will be given a secret code name so that no-one will know how you do in the tests, except us. We will keep the code name in a safe place.

If you ever get worried about anything, you can tell me or your parents. You can always change your mind about doing this and no one will be upset with you. All you have to do is to tell your parents or me.

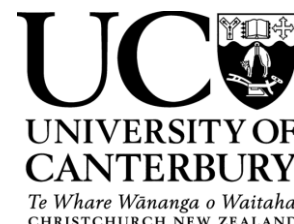
I hope you would like to help with my project!

Patricia

APPENDIX G

Parent Consent Form (Control Group)

Department of Psychology
University of Canterbury
Private Bag 4800
Christchurch



Boosting numeracy using "The Number Race" Consent Form for Parents and Guardians

I have been given a full explanation of this research project and an opportunity to ask questions.

I understand what will be required of me and my child if I agree to take part in this project.

I understand that my child's school will provide my child's numeracy and literacy achievement data for 2012 and 2013 to the researchers as part of the project.

I understand that my participation is voluntary and that I or my child may choose to withdraw at any stage without penalty. If I do so, the researchers will do their best to remove any information relating to me and my child.

I understand that any information provided by myself, my child, and my child's school will be kept confidential to the researchers involved with the project and that any published or reported results will not identify me or my child.

I understand that all data collected for this study will be kept in locked and secure facilities and/or in password protected electronic form, and will be destroyed after five years.

I understand that there is a small risk that the tests in the study might make my child feel anxious, and that if this occurs the researchers will discuss this with me.

I understand that if I require further information, or that if I would like a copy of the findings of the study, I can contact either Patricia Kant, or her supervisor, Dr Anna Wilson.

If I have any complaints I can contact the Chair of the University of Canterbury Educational Research Human Ethics Committee.

By signing below I agree for my child to participate in this research project.

Name: _____ Date: _____

Signature: _____

Email address:_____ Phone:_____

I am happy for my child's results to be given to his/her school ☐ Yes ☐
No

APPENDIX H

Child Consent Form (Control Group)

Department of Psychology
University of Canterbury
Private Bag 4800
Christchurch



Boosting numeracy using "The Number Race" Consent Form for Children

My mum or dad (or guardian) has told me about your project.

I am happy for you to do some tests with me at school at the beginning and at the end of term.

I know that you won't tell anyone else about how I do, except my parents (and also my teacher if my parents say that's ok).

I understand that the things you find out about me will be kept safe.

I know that if anything makes me feel worried, I can tell you or my parents about it.

I understand that I can always change my mind about doing this and no-one will be upset.

I know that if I have any questions I can ask you or my parents.

Child's name: _____

Signed by child (or on behalf of child): _____

Date: _____

PLEASE RETURN THIS SIGNED FORM TO SCHOOL

APPENDIX I

Parental Questionnaire

Parent Questionnaire: Boosting numeracy using “The Number Race”

Date: _____

Child's name: _____

In this questionnaire we will ask you questions about your child's learning, development, and medical history, as well as demographic questions about yourself and your partner. The questions are all on things that can sometimes relate to learning, but not always, and not necessarily for your child. If you do not want to answer a particular question, that's fine, just leave it blank.

Please return the questionnaire to us in the enclosed pre-addressed envelope. Thank you so much for taking the time to complete this questionnaire!

Kind regards,

Patricia and Anna.

Child questions:

1. Is your child left or right handed? _____

Child: Learning

2. Has your child always been to preschool and school here in New Zealand?

☐ Yes ☐ No

If No, please note whereabouts, at what age, how long for, and language of instruction:

3. How many hours a week did your child attend childcare/preschool/kindergarten?

Age	Childcare/preschool	Kindergarten
1 yr		
2 yrs		
3 yrs		
4 yrs		

4. Has your child ever been home schooled, or absent from school for a long period?

☐ Yes ☐ No

If Yes, please note at what age, how long for, and reason:

Was your child behind in his/her development any of the following? (e.g. noted by Plunket)

- a. Walking (13 months) ☐ Yes ☐ No
- b. Talking (1-2 years) ☐ Yes ☐ No
- c. Eye contact and social interaction (6-12 months) ☐ Yes ☐ No
- d. Fine motor skills (manipulating objects) or motor coordination (ongoing) ☐ Yes ☐ No

If yes, please describe. Note any associated diagnoses or remediation given (e.g. speech therapy).

5. Is English the only language your child can speak / understand? ☐ Yes ☐ No

If No, when did your child first start speaking English? _____ years

What language(s) was he/she was exposed to in the first year of life)?

Please list the languages other than English that your child understands/speaks:

Language	Age learned	Level:
a.		<i>understands only.....speaks a little.....speaks well</i>
b.		<i>understands only.....speaks a little.....speaks well</i>
c.		<i>understands only.....speaks a little.....speaks well</i>

6. How do you think your child is going with maths, reading and writing?

If your child is experiencing difficulties, please describe them below:

7. How often do you read to your child or count with him/her? _____ times per week

How often do you count with him/her? _____ times per week

How often do you help your child with his/her homework? _____ times per week

Child: Medical

8. Has your child ever had his/her hearing and vision tested? ☐ Yes ☐ No

Note any issues that were found below:

9. Has your child ever been given ongoing medication (for more than a month)? ☐

Yes ☐ No

If Yes, please note what for below:

10. Has your child ever had a head injury that required hospitalisation? ☐ Yes ☐ No

If Yes, how did the injury occur?

How long was the hospitalisation?

Was there any concussion? How long for?

What was the outcome of any brain scans taken?

11. Has your child ever had a seizure? ☐ Yes ☐ No

If Yes, please note when, how frequently, and if there is any related diagnosis:

12. Was your child born close to his/her due date? ☐ Yes ☐ No

If No, how many weeks premature or late? Was there any associated treatment (e.g. ICU)?

13. What was your child's birth weight? _____ kg

14. Were there any complications during the pregnancy with your child?

If Yes, please describe:

15. Were there any complications when he/she was born? ☐ Yes ☐ No

If Yes, please describe (e.g. hypoxia, foetal distress):

16. Can you think of anything else about your child that it might be useful for us to know?

17. Do you think anyone else in your family (immediate and extended) might have or had a learning difficulty in maths or reading? ☐ Yes ☐ No

If yes, please list relation (e.g. brother, mother, grandfather cousin etc.) and area(s) of difficulty:

Parents: Demographic

18. Mother's occupation: _____

19. Mother's highest level of education:

- ☐ Below 5th form
- ☐ 5th form (Year 11)
- ☐ 6th form (Year 12)
- ☐ 7th form (Year 13)
- ☐ Technical training
- ☐ Some university
- ☐ Bachelors degree
- ☐ Postgraduate degree(s)
- ☐ Other – *Please describe:*

20. Father's occupation: _____

Father's highest level of education:

- ☐ Below 5th form
- ☐ 5th form (Year 11)
- ☐ 6th form (Year 12)
- ☐ 7th form (Year 13)
- ☐ Technical training
- ☐ Some university
- ☐ Bachelors degree
- ☐ Postgraduate degree(s)
- ☐ Other – *Please describe:*

Thank you for your help!

APPENDIX J

Stimuli Details

1. Enumeration Stimuli

The following two tables present the stimuli used for the enumeration task for both sets of trials and whether the numerosity presented was in the subitizing range (S) or the counting range (C). Table is continued on next page.

Set 1:

Set	Numerosity	Correct Response	Range
1	3	3{ENTER}	S
1	5	5{ENTER}	C
1	1	1{ENTER}	S
1	7	7{ENTER}	C
1	5	5{ENTER}	C
1	4	4{ENTER}	C
1	6	6{ENTER}	C
1	2	2{ENTER}	S
1	7	7{ENTER}	C
1	1	1{ENTER}	S
1	6	6{ENTER}	C
1	4	4{ENTER}	C
1	2	2{ENTER}	S
1	1	1{ENTER}	S
1	6	6{ENTER}	C
1	2	2{ENTER}	S
1	7	7{ENTER}	C
1	4	4{ENTER}	C
1	6	6{ENTER}	C
1	3	3{ENTER}	S
1	5	5{ENTER}	C
1	2	2{ENTER}	S
1	3	3{ENTER}	S
1	1	1{ENTER}	S
1	4	4{ENTER}	C

Set 1 continued:

1	7	7{ENTER}	C
1	5	5{ENTER}	C
1	3	3{ENTER}	S

Set 2:

Set	Numerosity	Correct Response	Range
2	1	1{ENTER}	S
2	5	5{ENTER}	C
2	3	3{ENTER}	S
2	6	6{ENTER}	C
2	5	5{ENTER}	C
2	7	7{ENTER}	C
2	1	1{ENTER}	S
2	4	4{ENTER}	C
2	3	3{ENTER}	S
2	2	2{ENTER}	S
2	6	6{ENTER}	C
2	5	5{ENTER}	C
2	3	3{ENTER}	S
2	2	2{ENTER}	S
2	4	4{ENTER}	C
2	7	7{ENTER}	C
2	2	2{ENTER}	S
2	1	1{ENTER}	S
2	7	7{ENTER}	C
2	4	4{ENTER}	C
2	2	2{ENTER}	S
2	5	5{ENTER}	C
2	3	3{ENTER}	S
2	6	6{ENTER}	C
2	1	1{ENTER}	S
2	4	4{ENTER}	C
2	7	7{ENTER}	C
2	6	6{ENTER}	C

2. Number Comparison (Symbolic Task) Stimuli

The following table presents the stimuli used for the number comparison task.

Digit 1	Digit 2	Distance	Correct Key	Log Ratio	Ratio Category
7	2	5	f	1.252763	1.45
6	1	5	f	1.791759	1.45
5	7	2	j	0.336472	0.46
2	1	1	f	0.693147	0.79
5	3	2	f	0.510826	0.46
6	9	3	j	0.405465	0.46
7	3	4	f	0.847298	0.79
4	9	5	j	0.81093	0.79
5	6	1	j	0.182322	0.2
9	8	1	f	0.117783	0.2
7	4	3	f	0.559616	0.46
2	5	3	j	0.916291	0.79
4	1	3	f	1.386294	1.45
3	8	5	j	0.980829	0.79
2	6	4	j	1.098612	1.45
8	4	4	f	0.693147	0.79
2	9	7	j	1.504077	1.45
3	6	3	j	0.693147	0.79
7	9	2	j	0.251314	0.2
8	2	6	f	1.386294	1.45
7	6	1	f	0.154151	0.2
4	2	2	f	0.693147	0.79
7	8	1	j	0.133531	0.2
4	5	1	j	0.223144	0.2
8	1	7	f	2.079442	1.45
2	3	1	j	0.405465	0.46
6	4	2	f	0.405465	0.46
8	5	3	f	0.470004	0.46
3	9	6	j	1.098612	1.45
6	8	2	j	0.287682	0.2
5	9	4	j	0.587787	0.46
4	3	1	f	0.287682	0.2

3. Numerosity Comparison (Non-Symbolic Task) Stimuli

The following table presents the stimuli used for the numerosity comparison task. The first two columns refer to the number of dots presented. Table is continued on next page.

n1	n2	Ratio	Log Ratio	Ratio Category	Correct Response
16	10	0.63	0.47	1	f
16	10	0.63	0.47	1	f
16	12	0.75	0.29	2	f
16	12	0.75	0.29	2	f
16	14	0.88	0.13	3	f
16	14	0.88	0.13	3	f
16	18	0.89	0.12	4	j
16	18	0.89	0.12	4	j
16	22	0.73	0.32	5	j
16	22	0.73	0.32	5	j
16	26	0.62	0.49	6	j
16	26	0.62	0.49	6	j
32	20	0.63	0.47	1	f
32	20	0.63	0.47	1	f
32	24	0.75	0.29	2	f
32	24	0.75	0.29	2	f
32	28	0.88	0.13	3	f
32	28	0.88	0.13	3	f
32	36	0.89	0.12	4	j
32	36	0.89	0.12	4	j
32	44	0.73	0.32	5	j
32	44	0.73	0.32	5	j
32	52	0.62	0.49	6	j
32	52	0.62	0.49	6	j
10	16	0.63	0.47	6	j
10	16	0.63	0.47	6	j
12	16	0.75	0.29	1	j
12	16	0.75	0.29	1	j
14	16	0.88	0.13	5	j
14	16	0.88	0.13	5	j
18	16	0.89	0.12	2	f
18	16	0.89	0.12	2	f
26	16	0.62	0.49	3	f
26	16	0.62	0.49	3	f
18	16	0.89	0.12	4	f
18	16	0.89	0.12	4	f
20	32	0.63	0.47	1	j

Table continued:

n1	n2	Ratio	Log Ratio	Ratio Category	Correct Response
20	32	0.63	0.47	1	j
24	32	0.75	0.29	2	j
24	32	0.75	0.29	2	j
28	32	0.88	0.13	3	j
28	32	0.88	0.13	3	j
36	32	0.89	0.12	4	f
36	32	0.89	0.12	4	f
44	32	0.73	0.32	5	f
44	32	0.73	0.32	5	f
52	32	0.62	0.49	6	f
52	32	0.62	0.49	6	f

4. Number Line Stimuli

The following two tables present the stimuli used for the enumeration task for both sets of trials.

Set 1:

Block	Number
1	8
1	3
1	5
1	9
1	4
1	1
1	6
1	2
1	7

Set 2:

Block	Number
2	3
2	9
2	6
2	4
2	1
2	5
2	7
2	2
2	8